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AERONAUTICS AND AIR TRAFFIC CONTROL

by G. B. Litchford

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16. Abstract

A study and evaluation is made of the broad aspects of air traffic control and its relationship to the future of aeronautics. Present ATC techniques of controlling air traffic primarily by ground personnel are compared with new concepts wherein the pilot becomes a more active participant in the air traffic control process.

Adequate progress in ATC cannot be expected until far better testing, validation, and design tools become available. Some candidates for new national facilities for testing various aspects of ATC and related aeronautics are identified.

ATC technology in its broadest sense is essentially emerging as a new professional area. New programs and courses in ATC technologies are needed in curricula of colleges and universities to produce sufficient numbers of qualified graduates.

Improved communications between the diverse disciplines impacting ATC progress is essential. Often a given government agency represents but a few of the many disciplines involved. It is urged that an improvement in the application of the total government resources in ATC technology be made.

The fractional elements within government, industry, and the universities required for the solution of ATC technology can be brought together and focused on a progressive national solution.

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AERONAUTICS AND AIR TRAFFIC CONTROL

SYNOPSIS

A study and evaluation is made of the broad aspects of Air Traffic Control (ATC) and its relationship to the future of aeronautics. Present ATC techniques of controlling air traffic primarily by ground personnel are compared with new concepts wherein the pilot becomes a more active participant in the air traffic control process. These new ATC concepts will require some changes in navigation, guidance and control, data exchange, and aircraft operations. However, the new concepts offer potential for much greater system capacities to cope with the existing and rapidly growing air traffic problems. Additional goals besides increased capacity are: (1) more services at lower costs; (2) ATC services that are more equitable available to all airspace users; and (3) services more suited to a wide spectrum of environments.

More emphasis on the pilot's participation and responsibilities in ATC is a complex subject and does not imply the transfer of full responsibility for ATC to the cockpit. Rather, a new balance between pilots and controllers must be developed. Suggested ATC concepts of "broadcast-control," which give the pilot new functions in dense traffic, are balanced with current "close-control" concepts. This places emphasis on understanding the pilot's ATC skills and limitations, new pilot instruments or displays for executing specific ATC functions in the cockpit, and the engineering of new ATC operations related to the response and limitations of the wide spectrum of new aircraft. Effectively, more "rate" information is added to a (air traffic) control system, that predominantly employs "displacement" information in its current control functions. Several technical areas associated with these and other concepts of ATC are discussed in Sections II, III, and V.

To solve our ATC problems, the "ATC engineer" needs new "tools" for design of future ATC systems and equipments. The ATC engineer's needs for test and validation methods are

barely recognized today. For example, few if any ATC test facilities exist that are equivalent in number, cost, and quality to the dozens of sophisticated wind tunnels the aeronautics engineer employs in creating his professional products. The nation's missile and rocket test facilities are another example of how a new technology prospered by using "tools" for scientifically validating designs and concepts. Adequate progress in ATC cannot be expected until far better testing, validating, and design "tools" become available. Some candidates for new national facilities for testing various aspects of ATC and related aeronautics are identified in Section IV.

Improved communications between the diverse disciplines impacting ATC progress is essential. The skills and disciplines of controllers, electronics, pilots, aeronautics, airport-design, system-engineering, flight-control, pilot displays, regulatory, legal, safety, and economic aspects must <u>all</u> be integrated for solving the nation's ATC problems. Section III relates eight areas of ATC to a total-aviation system concept. Often a given government agency represents but a few of the many disciplines above. It is urged that an improvement in the application of the total government resources in ATC technology be made, as no monopoly on solving ATC problems exists.

ATC technology in its broadest sense is essentially emerging as a new professional area, with some 40 billion dollars per decade now planned for operation and use of the nation's ATC system. New programs and courses in ATC technologies are needed in the curricula of colleges and universities to produce sufficient numbers of qualified graduates at all levels (including PhD) to cope with current and future ATC problems. A much better organized and scientific approach toward ATC technology is needed, and this can come about, at least partially, by a coordinated effort in several recognized colleges and universities that have complementary educational programs. Existing aviation programs in four universities are reviewed and suggestions made in Section VI as to the means for accelerating and improving the national level of producing professionally trained scientists and engineers in the ATC technologies. Professional training in "total-systems" approach to massive systems and urgent problems of the real world of air traffic control would be the goals of a NASA-sponsored university-ATC program.

The many interfaces of NASA's aeronautics activities with other agencies, particularly DOT, are noted in Section VII, and several recommendations are made for joint programs in air traffic technologies. The many resources of NASA in the way of personnel, facilities, and skills that can be applied to the nation's ATC problems should be related to the similar resources of other agencies and industry. Even with all resources combined, it is quite possible that the total R & D resources that are especially suited to this area are <u>not</u> commensurate with the magnitude of the problems ahead in ATC technology for the next two decades. The solution to ATC technology now appears to hold the key to aviation's future. With enough effort, the fractionated elements within government, industry, and the universities required for its solution can be brought together and focused on a progressive national solution.

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I. INTRODUCTION

Although NASA is best known for its outstanding record in space, it has for many years had a continuing program in aeronautics. In fact, its predecessor organization, the National Advisory Committee for Aeronautics (NACA), was devoted from its inception to aeronautics. With the advent of the space age, NASA was created to realize the goals of a ten-year national space plan; these goals have been fully realized.

Although space will continue to play an important part in NASA's future, the aeronautics function of NASA (the first "A" stands for aeronautics) is becoming increasingly challenging because of the many innovations in aviation. The broader term "aviation" is used here to indicate that the aircraft is no longer just an entity in itself; rather, it is a vehicle that is no more useful to society than its ability to operate in a modern environment of high-density air traffic, low visibility, at low noise levels, and with outstanding regularity and safety.

The study that is discussed in this report examines the environment of the modern aircraft so that the full meaning of "aeronautics" is appreciated. The field of modern aeronautics encompasses more than just power plants, airframes, aerodynamics, wind tunnels, etc.; it now includes the total environment in which the aircraft and its pilot must operate. Much of this environment requires precise control of aircraft flight patterns and is thus electronic in nature.

Radio guidance and control from many different types of ground and air sources is needed today; this requires several thousand ground facilities. Communications, identification, and other means of permitting the modern aircraft and its pilot to operate in today's airspace are no longer "aids" but basic essentials. When only a few aircraft were operating, say, 30 to 40 years ago, the control of air traffic was a minimal problem, since the probability of collision was small, and the aircraft were so slow and maneuverable that big airports were unheard of. Other competitive forms of transportation were then available that no longer exist. These other transportation forms are now (in the '70's) time-consuming or uneconomic, placing a larger national responsibility on aviation from now on.

A. RELATIONSHIP OF ATC AND AERONAUTICS

Webster describes aeronautics as "The science that deals with the operation of aircraft," and "The art or science of flight. . . ." These definitions are still adequate--that is, they encompass the impact of several aircraft using a common airspace, which has created a new and important aspect of aeronautics. This "new" aspect of aeronautics that deals with the operation of aircraft in limited amounts of airspace is as significant to aviation as the past, more limited concepts of aeronautics. Furthermore, many of the older or more basic aeronautics issues are well understood, and a storehouse of knowledge and facilities exists for their continued exploitation, such as wind tunnels, test chambers, structural test facilities, flight research centers, etc. The "new" aspect of aeronautics, which deals with the aircraft in various ATC environments, is relatively barren of equivalent test facilities and lacks much needed validated data.

Thus, since the early days of operationally useful aviation--some 50 years ago--the nature of aeronautics has changed markedly, and its future is now closely tied to improvements in air traffic control, airports, landing systems, etc., much as when it was initially dependent on developments in airframes and power plants. A scientific approach to this phase of aeronautics requires a new school of scientists and the construction of test facilities if viable ATC solutions are to be realized. R & D is essential in aeronautics related to ATC if the lack of a suitable combination of disciplines is not to become a barrier to aviation progress.

Without this new and broader concept of "aeronautics" the future of aviation will be sterile. The factors of runway lengths, dense traffic noise, fog landings, safety, aircraft collision prevention, etc., have combined in the past few years to introduce a new concept of aeronautics. It is the objective of this study to illuminate the nature of these new aspects of aviation and aeronautics and to emphasize some important new interfaces that now exist between aircraft flight and the ATC system.

Aeronautics has not been usually considered to include those environmental conditions that are mostly electronic. However, they now impact so strongly on the vehicle itself that no longer can aircraft be designed or operated without nearly equal attention being given to these new ATC-aeronautic factors as was previously given to such classical matters as airframes and power plants. In fact, the classical technological aspects are so far advanced today that nearly any type of aircraft can be designed and its costs and flight characteristics almost fully predicted before it actually flies--that is, classical aeronautics is now far more scientific than it was 30 or 40 years ago. Consequently, we can now confidently conceive and build aircraft that will do nearly anything that society requires. We cannot do this in ATC technology. In fact, the supporting environmental aspects that are now so essential to aeronautics--such as ATC, airports, communications, navigation--are far from this stage of advanced development and are indeed the barriers to aviation progress, just as power and structures were a short time ago. By concentrating in the decade of the '70's on this problem of creating a Total Aviation System of Aeronautics-ATC as a national goal, similar to our space goals of the '60's, we can realize success. A fragmented program will fail. The "new" aeronautics will encompass the full breadth of the meaning of the "science-of-flight;" we can overcome these barriers of ATC and related matters just as we have, in the past, overcome other aviation barriers.

B. A BROADER CONCEPT OF AERONAUTICS

This report identifies several areas where the "science-of-flight" now encompasses all aspects of aeronautics, including, for example, air traffic control. Such an example is low-visibility landing, where the optimized combination of pilot, cockpit displays, aircraft controls, and a new radio landing guidance system is essential to the solution of this aspect of the science of modern flight.

No longer will only visual flight be adequate, since it would restrict the regularity and safety of air transport to such an extent as to seriously degrade its value. With modern aircraft speeds and traffic density, the "see-and-be-seen" and "see-to-land" aspects of early aviation are a thing of the past. Smog and recent environmental limitations and the desire to operate in low visibility have reduced the ability to "see" adequately for track guidance and to avoid obstructions and other aircraft, but visual aids using controlled lights and optics are still required to supplement radio transmissions--both are essential.

Modern electronics, thus, is as essential to the present and future operation of an aircraft as the engine or the wings and now must be as fully understood and included in our modern concepts of aeronautics. In fact, the impact of the modern aircraft on the electronics (that guide and control it) is about equal to the impact of the electronics on the aircraft itself. This is true not only operationally but economically, because aviation electronics is now a major part of the total cost of aeronautics and is on the increase.

This report identifies and develops those areas whose extensive capabilities can best be applied to broaden and advance the science of aeronautics. Particular emphasis is placed on ATC because it is considered the most significant aspect of aeronautics for at least a decade and possibly longer. Large national commitments to new aircraft, airports, and airways having a total cost of possibly 200 billion dollars are evidence of aviation's acceptance and importance to our society. These enormous commitments are dependent on solving new, often unrecognized interfaces between aircraft and electronics, the pilots and the controllers, the visibility and cockpit instruments--all treated but in a nominal manner in the past.

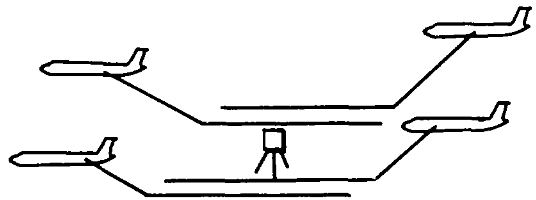
In fact, part of today's ATC "crisis" can be traced to the independent route of "classical" aeronautics and the independent route of aviation electronics, which have been separately pursued in the past. These independent practices are as archaic in the

'70's as the DC-3 and DC-4. Even so, many of our navigation and ATC concepts and devices stem from that era. We must now focus on the broader concepts of aeronautics. Assuming that many of our structure and propulsion problems are behind us, the future of aeronautics lies in the operational application of modern aircraft in a complex electronic and airport environment not envisioned 20 years ago.

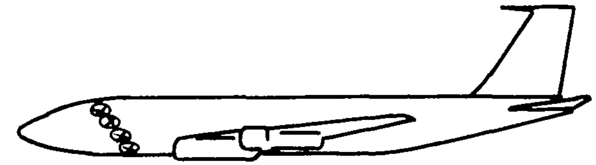
C. ATC MAY DETERMINE AVIATION'S FUTURE

The modernization of our aviation facilities (mostly electronic) to suit the types and quantities of aircraft, to suit the wide spectrum of airframe costs, and to reduce ATC operating expenditures is important. What can be a defeating financial burden of continuing to add thousands of employees and thousands of separate new ground (ATC) facilities can as surely stifle aviation as if all airlines were forced to operate only DC-3's. Without a thorough assessment or test of newer concepts, there is little hope of gaining large improvements in system capacity at lower costs. Examples of candidates to achieve this are (1) Wide Area-Nav using, say, 4 or 5 stations to cover the nation rather than over 1,000 stations, (2) the use of microwaves for landing guidance rather than cumbersome VHF signals, (3) creating a general aviation (GA) capability of IFR at extremely low (relative) costs and suited to dispersed locations of thousands of GA airports, and (4) providing greater pilot participation in ATC by improved concepts of cockpit displays. Figure 1 summarizes these potentials.

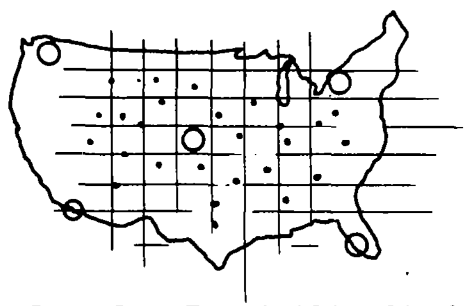
The use of modern simulation and validation tools designed for ATC R & D--just as our missile test ranges and wind tunnels are used--is essential to aeronautics progress. The goal is to validate such critical matters as low-visibility landing and how to design a modern jetport; validation must take place before the fact--that is, before the decision process creates a commitment to implement. Quantitative assurance and technical knowledge of operational performance will be available for decisions rather than simply building another costly ATC facility.



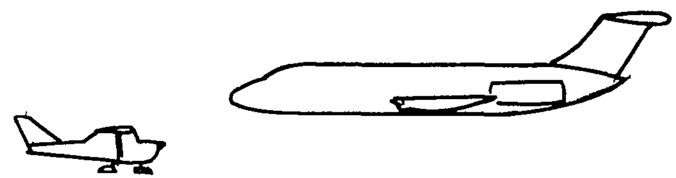
SCANNING BEAM ILS
°Closer runway spacing
°Curved noise abatement paths
°CAT III capability
°Increased airport capacity
°Civil-military configurations using a common signal standard
°Flexibility in costs and services
°Fixed and portable versions



IMPROVED COCKPIT CAPABILITY IN ATC
°Better pilot-controller relation
°Area-Nav displays
°Volumetric landing display
°Air-to-air display of common track spacing and proximity
°Air-to-ground air-to-air data exchange
°Reduced controller functions
°Pilot display of track speed



LF or VLF WIDE AREA-NAVIGATION SYSTEM
°4 to 5 stations rather than over 1,000
°Oblique-parallel geometrics
°No DME--receive only
°Low-cost air and ground systems
°Coverage to surface
°Constant granularity
°Lower maintenance and user costs
°Uniform coordinates at all 10,000 airports



COMPATIBLE GENERAL AVIATION FACILITIES
°Very very low-cost Area-Nav
°Transponder-VOR
°Signal for air-to-air proximity
°Minimum ATC services at thousands of dispersed airfields
°VLF or LF roll-call position reporting suited to flight and cost constraints
°Simplified pilot participation in ATC

EXAMPLES OF INCREASED SYSTEM CAPACITY
FOR LOWER UNIT COSTS

FIGURE 1

We are actually in the "trial-and-error" stage in many aspects of ATC, in spite of the assurances of many publications and simplified analyses that suggest the contrary. Obtaining quantified data based on tests in true environmental conditions with real aircraft is essential in the new rounds of ATC development. We must assure that aeronautics in its broad sense is being developed and not just another aircraft or another electronic system; the interface between the two may not work well at all if each is done in isolation as in the past. The future developments of ATC must also avoid the practice of skipping full validation and going directly to testing while operating "on-line." Public safety or inconvenience is now at stake. Although "on-line" testing, using the actual or modified ATC system, was a small decision in the past history of ATC, it is a practice that has a tendency to be carried forward. In addition to public risk or inconvenience in case of failure, these "on-line" tests cannot yield scientifically acceptable data, since the tests cannot be scientifically controlled during normal ATC operations. One important example of this "on-line" testing is the lowering of landing visibility authorizations by actual airline experience, carrying airline passengers in lower and lower visibility conditions. Rather than this practice, which is non-productive of quantified, valid data, an independent testing and validation program utilizing national test resources not involving public risk is preferable. Adequate facilities for such a program are available from several government agencies and especially NASA.

In the new aviation environment, a commitment as great as 150 billion dollars for aircraft being dependent on these poorly tested concepts is no longer acceptable. Before applying new ATC concepts or facilities to the actual ATC environment, they must be scientifically proved by new means of validation. Several new national test facilities must be developed early in the ATC modernization program to validate the developments that are already obvious. "On-line" ATC testing is a thing of the past.

II. THE NATURE OF THE NATIONAL AVIATION SYSTEM

Several recent reports (see Table I) permit a clearer view of the effort required to operate and modernize the existing systems of ATC, Navigation, Landing, Airports, VSTOL, etc., that compose the current national aviation system. Most of these plans are based on technology of currently operating systems and equipments. Furthermore, the potential of some new concepts, techniques, and systems for adding system capacity and perhaps for providing more services per unit cost are emerging. A good example of the modernization and operation of current ATC systems is contained in the FAA report, THE NATIONAL AVIATION SYSTEM PLAN-TEN YEAR PLAN(1), dated March 1970. An example of some new concepts is given in the report of the DEPARTMENT OF TRANSPORTATION AIR TRAFFIC CONTROL ADVISORY COMMITTEE (known as the ATCAC report or the "Alexander" report, after its chairman). There are several other reports completed or in progress, such as the ATA, FAA, and SRDS reports, and the "National Aviation System Policy Summary." Work of interagency advisory groups such as the several special committees (SC) of the Radio Technical Commission for Aeronautics (RTCA), also aid in projecting several special areas such as a new microwave landing system (SC-117).

Many other reports exist within given agencies, or as inter-agency matters (such as the DOT-NASA CARD committee) and the National Academy of Engineers ad-hoc committees. The Congress has issued several reports on hearings into aviation systems, ATC, user taxes, safety, etc. The various interdepartmental relations and, of course, the recent passage of the Aviation Trust Fund (Public Law 91-258) are further examples of the attention being given to this subject. This law, in principle, will establish by means of a user tax (as in the case of the highway funds) consistent sources of income for the operation and modernization of airways, ATC systems, and airports.

One convenient way to focus on the estimated magnitude of the ATC-Aviation system program for the next two decades is to

TABLE I

REPORTS ON OPERATION AND MODERNIZATION
OF NATIONAL AVIATION SYSTEM

	REPORT TITLE	AGENCY	REPORT CONTENT SUMMARY
I.	Report of Department of Transportation Air Traffic Control Advisory Committee Volumes I and II	DOT	Improved SSR system, new microwave scanning-beam ILS, and closely spaced multiple runways for increased traffic are noted. Satellites and collision avoidance systems are not recommended. Flight paths avoiding communities are possible with new guidance facilities, lowering noise-pollution. A data link to the aircraft using the SSR interrogate path is suggested.
II.	The National Aviation System Plan 1971-1980	FAA	A detailed summary of the many elements that make up the current system and their increase in numbers or performance levels. FAA manpower and facilities are estimated, costing about 18 billion dollars for ten years. This is a well presented document portraying the current FAA thinking on ATC facilities and related matters.
III.	The National Aviation System Plan - Policy Summary	FAA	This report complements the above report in describing the systems operation as viewed by the FAA. Present and future concepts of navigation, traffic control, and airport developments are given.
IV.	Civil Aviation R & D Policy Study (under preparation)	DOT/NASA	A broad review of civil aviation R & D is undertaken to identify the public benefits from aviation, its costs and its relation to a "total" transportation system. The impact of new aeronautics and electronic technology is to be examined and a recommendation made to appropriate agencies and Congress for a national plan for aviation. The vehicle, airports, and ATC are identified as major interfaces of aviation.

	REPORT TITLE	AGENCY	REPORT CONTENT SUMMARY
V.	Recommendations for a National Air Traffic Management System	Air Transportation Association of America (ATA)	A report by this airline group on their views on how today's ATC system should be "remodeled" to handle safely and efficiently the expected growth of aviation. Several recommendations are made relating to Area-Nav, collision avoidance, airspace designations, data link, automated SSR-data processing, etc.
VI.	Civil Aviation Research and Development: a. Air Traffic Control b. Airport and Support Facilities c. Economics of Civil Aviation d. Aircraft noise e. Problems and recommendations	Aeronautics and Space Engineering Board (of the) National Academy of Engineering	The many problems of civil aviation are assessed and recommendations made that their solutions be undertaken, including preferred assignments to agencies such as NASA and DOT. This report notes that the FAA is oriented primarily toward regulatory and operational aspects. Sources of new technologies (coming from DOD and NASA) are needed as are expanded and broadened aeronautic responsibilities for NASA.
VII.	Air Transportation 1975 and Beyond--A Systems Approach	The Transportation Workshop (reported by the MIT Press)	Air transportation experts from government and private sectors joined in an "ad-hoc" study of air transportation. Six panels on socio-economics, air vehicles, ATC, airports and terminals, mixed-modes, and government policies prepared sections of the final report. Several areas are well illuminated with charts and notations. This 500-page book gives a good overview of aviation's problems.

	REPORT TITLE	AGENCY	REPORT CONTENT SUMMARY
VIII.	U. S. Congress a. Policy planning for aeronautical R & D b. Issues and directions for aeronautical R&D c. Aeronautical R & D policy d. Aeronautical research e. Aviation facilities maintenance and development f. Administration's proposal on aviation user charges g. Problems confronting the FAA in the development of air traffic control systems for the 1970's h. Federal transportation expenditures	Selected Committee reports of the House and Senate	These reports provide many insights into the views of the Congress and Administration relating to aviation, aeronautics, and ATC. The costs of R & D are reviewed by these committees. It is noted that a "national plan" for aviation and its relation to other forms of transportation is required. The aviation views of federal agencies, industry, state governments, airlines, pilots, military, and general aviation are more readily reviewed in the many reports of the Congress than elsewhere. The interest and concern of Congress about aviation and ATC are very apparent.
IX.	Department of Defense Impact on the National Air Traffic Control System (AIAA paper 69-1113)	DOD Office of the Secretary of Defense	This DOD paper is one of the few available that summarizes the Defense Department view of ATC. Military aircraft must use a system of ATC that is "common" with that of the civil users in the U.S., and this is extended wherever possible overseas to avoid aircraft and ground units supporting two separate ATC systems. The large impact of DOD for at least one to two decades more is outlined as well as their large investments in a common ATC system, and their plans to assist with new terminal area and landing system developments. The nearly 400 airports, 30,000 aircraft, and perhaps 30,000 personnel associated with only DOD's portion of ATC is significant in any national plan. DOD resources to aid in a national ATC system are pledged.

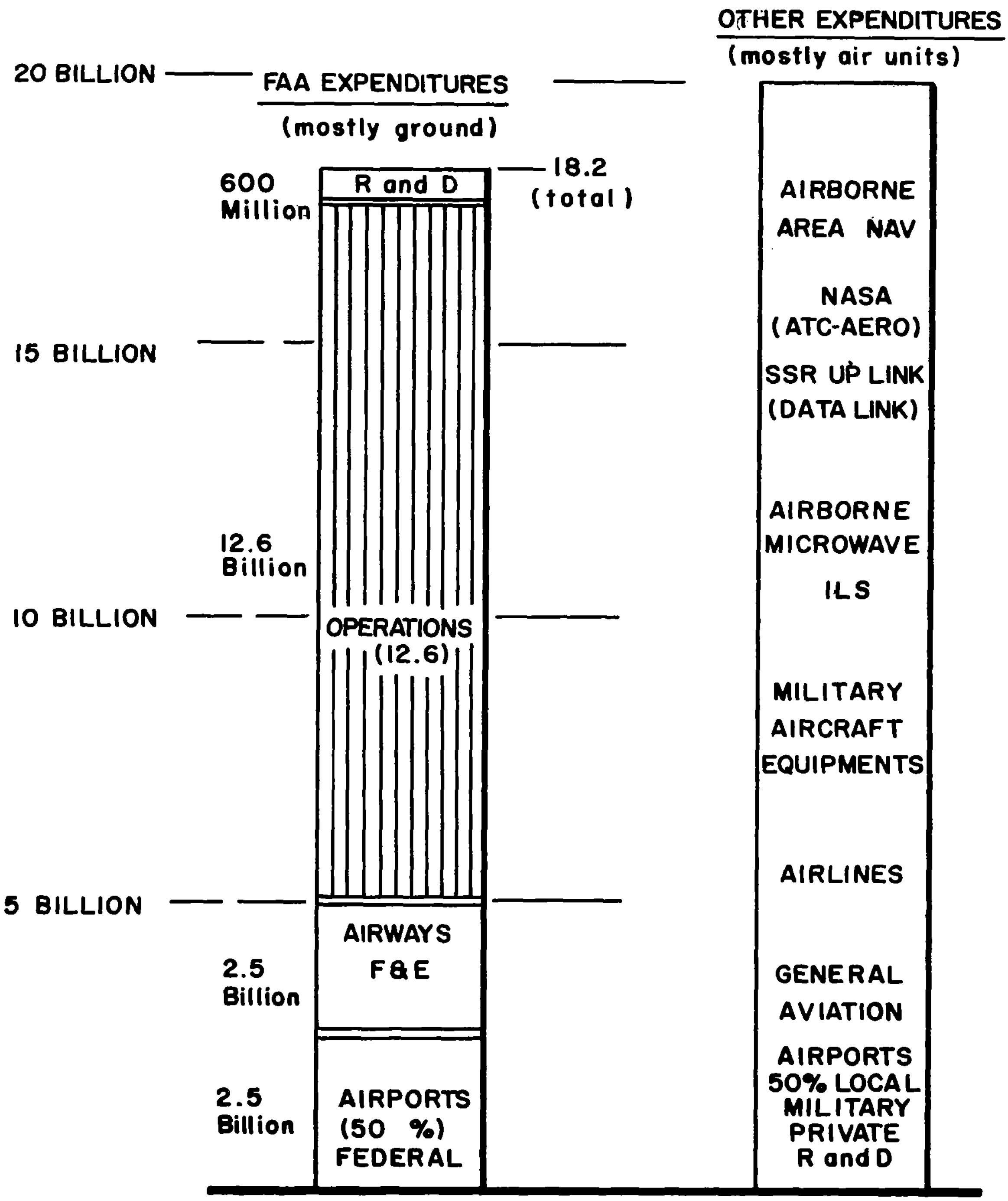
	REPORT TITLE	AGENCY	REPORT CONTENT SUMMARY
X.	Northeast Corridor VTOL (VSTOL) Investigation	CAB	The use of VSTOL aircraft in the Northeast Corridor of the United States is examined and the need and feasibility for these aircraft are evident. Relief from congestion and overloads of ATC and airports in New York alone would prevent what was estimated by some to be a 500 million dollar per year loss to New York's economy. Airports, air traffic control, and the vehicle were identified as the technical items that could lead to off-loading major jetports by diverting from 20% to 40% of the passengers to VSTOL airports. VSTOL diversion essentially adds CTOL capacity and delays the need for costly CTOL airport expansion.
XI.	Microwave Scanning Beam Landing Guidance System Special Committee 117 (SC-117)	RTCA - Radio Technical Commission for Aeronautics	After some 30 months, all government agencies (and industry) prepared a plan for a new landing system. A recent (Sept. 5, 1970) report on a provisional signal format for a new multifunctional landing system contains a plan for starting R & D on a national basis. All users, at different economic levels; all vehicles, including small aircraft, VSTOL and CTOL; all airports from jetports to remote strips; and all military tactical needs can theoretically be satisfied by seven "configurations." The system is conceptually the 7 configurations using common CW carriers (C and Ku bands), common modulation (tone-CW) and common "dwell-times" for air data processing of many angle data signals in a single receiver.

review its estimated costs. The FAA "Ten Year Plan" summarizes the costs at 18.2 billion dollars for 1971-1980 (report I of Table I). This FAA document indicates the breakdown of costs in many categories and is perhaps as indicative of the current direction of effort as any. It effectively projects increased capacity by increasing the number of controllers, control sectors, radars, data automation, navigation and landing aids, communications and airports. This plan adds little that is new during this 1971-1980 period, but allows some funds for R & D of some new items such as a new Microwave Landing System, Collision Avoidance Systems, and Airport Surface Control facilities. The question of the adequacy of this R & D plan will be reviewed later.

Perhaps the two most interesting matters in the 18 billion dollar figure are what is included and what is not included. A total of 12.6 billion dollars is included for operation of the system by the FAA, reaching about 82,000 employees in 1980 of which about 46,000 are controllers and about 32,000 are associated with aviation facilities (installation and maintenance). Thus, as seen in Figure 2 by far the largest single FAA costs are operating costs. For example, R & D (FAA only) is estimated at 0.6 billion, airways at 2.5 billions, and airports at 2.5 billions (of a 5-billion dollar total--local governments supplying the other 2.5 billion). Figure 2 summarizes these and other costs.

A part of the total-national costs, but not included in this FAA figure, are the many additional costs that are as essential to a workable national plan as those estimated by the FAA. These non-estimated costs include the expenditures for the aircraft instrumentation that will be needed for increased capacity, such as Area-Nav, Data Links, New VORTAC (airborne equipments for Doppler-VOR, and new channelization), Microwave ILS receivers and transmitters, new pilot displays for new services, collision avoidance, and proximity warning units.

Another area of large costs related to the 10-year plan and the ATCAC plans includes the thirty thousand (approximately)



FAA AND OTHER EXPENDITURES FOR 1971-1980 TIME PERIOD AS ESTIMATED IN NATIONAL AIR TRAFFIC MODERNIZATION PLAN--ABOUT 40 BILLION DOLLARS IN THE NEXT TEN YEARS

FIGURE 2

military aircraft. Usually the Defense Department joins in the FAA implementation plans because of the use of "common system" concepts wherein non-tactical missions use "common" civil-military facilities here and abroad as much as practicable. This commonality is recognized in the FAA and trust fund legislation. Rather than a separate system for military ATC use, a common solution is proposed for ATC aids in military training and aircraft movements throughout the world (since ICAO and FAA standards are usually similar); this will obviously result in lower national costs.

Avoidance of jamming or radio interference between military and civil systems using the same rapidly dwindling radio channels is also quite essential. A few years ago a separate military system used the same radio band as a separate civil system, creating jamming and negating the value of both systems. Furthermore, civil and military aircraft could not use the other party's systems because of technical incompatibilities. Once this impasse was resolved after bitter and costly controversy, the "common" civil-military approach has usually prevailed in new plans. Commonality of civil-military ATC is a delicate balance, but it must be retained.

The Secondary Surveillance Radar (SSR) system of transponders and automated ground processing of aircraft transmitted data (identity, altitude, and position) for controller display is a modern example of how well a "common" system can work. If the DOT and DOD are encouraged to plan on common usage, procurement, testing, etc., commonality is assured. In the SSR case, both have benefited enormously from the joint effort, and this stands as a model for several upcoming ATC programs for these two users of the airspace.

However, the cost of outfitting the military aircraft fleet for using the common ATC facilities or any military ATC facilities is not included in the 18-billion dollar FAA figure, nor is the cost of outfitting the some 4,000 aircraft of the airline fleet. The 1971-1980 general aviation aircraft population is composed of many elements, but the owners of several thousand business jets and multi-engine aircraft (that operate similar to airliners and are as fully instrumented as most airliners) are also required to buy and install the many new electronic equipments in order to derive benefits from, and to comply with, the FAA plans for Area-Nav, New ILS, New VORTAC's, Data Links, etc. Some 150,000 to 200,000 single-engine aircraft will also require costly electronics for ATC during 1971-1980, adding to "other" costs.

Another area not included in the 18-billion FAA estimate is that the military will continue to operate many major bases here and abroad in which the 30,000 military aircraft operate. In the case of ATC, navigation, etc., they usually adhere to the same facilities as the FAA, but are budgeted in the DOD budget and would thus not be included in the FAA budget. This military cost would include about 13,000 controllers, an equal number of electronic-ATC maintenance personnel, almost 400 airports, and nearly a thousand facilities such as Radcons, RATLCS, TACAN, GCA, ILS radars, etc.

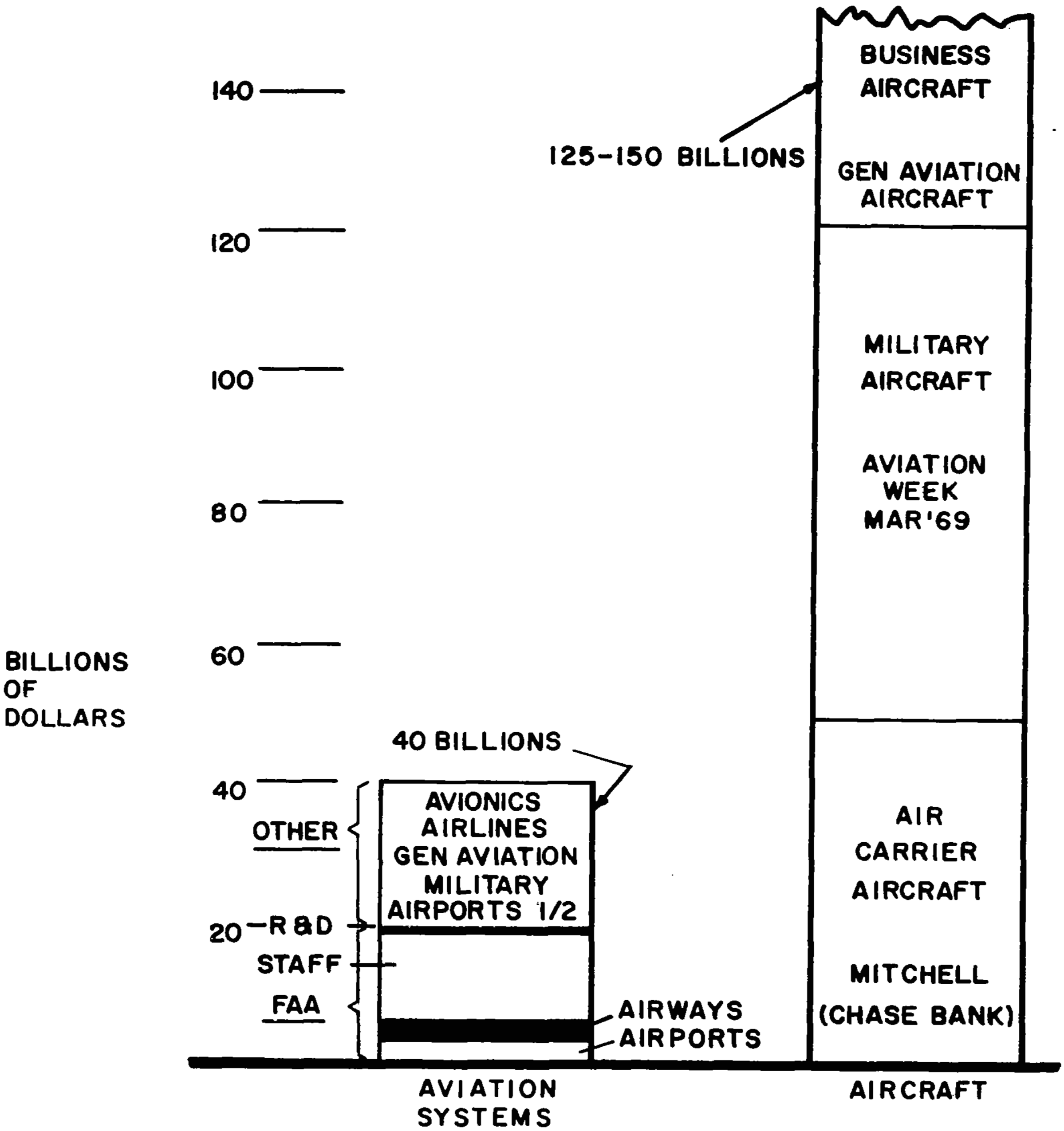
Although individually small, the some 150,000 to 200,000 single-engine and light-twin aircraft of general aviation (excluding the business aircraft noted above) are a large cost factor in the private sector since the addition of, say, several thousands of dollars of avionics to each aircraft is a part of our national ATC investment. As noted previously, the 2.5 billion dollars in local funds for airports (typical 50% matching funds from FAA) must be added to the FAA's 2.5 billion, totaling 5 billion to complete even a crude estimate of a total national cost for the program in the ten-year plan.

A. <u>TOTAL SYSTEM ESTIMATED COST IS 40 BILLION DOLLARS FOR 1971-1980</u>

Without further detailing the airline equipment costs, the military aircraft equipment costs, the military personnel and ground system costs, and the general aviation costs, it is quite likely that they will equal or exceed 18 billion dollars. Personnel costs for the military AACS and airline services are typical additional items, as is the inclusion of costly maintenance of airborne equipment and ground checkout equipments. Replacement of units during the ten years must also be considered. It is expected that many other activities budgeted in other areas will be essential to support such a large total national ATC program that is about half government and half private in its funding. Thus, in general, the total cost for the next decade of ATC will be about 40 billion dollars on a total national basis (Figure 3).

It is not likely that the costs in the 1980-1990 decade will be any lower, and they must also be considered since the national ATC and airport systems are continuing matters, not national projects that are slated for a given objective which, when realized, result in curtailment of spending such as often occurs in Space and Defense. As a matter of fact, the costs can be greater in the 1980-1990 decade, since keeping ATC running 24 hours daily and somehow adding new elements to greatly increase capacity is more costly than simply shutting a system down and replacing it. Several years of dual operation of the "old" and "new" are essential, totaling one or two decades before airborne units are fully compatible with the "new" ATC service.

Hopefully, new R & D outputs will provide some relief from overloaded ATC systems starting in 1975 but will extend into 1985 for full implementation. New airports, with concepts that inherently have much greater capacity for growth than the current ones, will aid the total capacity. The costly implementation of new ATC facilities, navigation aids, communications, and airports with automated surface control in the next (1980-1990) decade may increase the total costs beyond the 40 billions estimated for the present decade. Thus, an 80-billion dollar figure may be more realistic since a 20-year cycle is typical for aviation facility R & D, validation, procurement, implementation, operation, and user procurement of the associated airborne units and some ICAO standardization. Obviously, means for accelerating R & D and validation would accelerate the modernization; however, any attempt to circumvent full validation of such a complex system is dangerous and can cause faulty decisions.



RELATIONSHIP OF AVIATION SYSTEMS TO U. S. AIRCRAFT (1971-1980)

FIGURE 3

B. TECHNIQUES WITH MAJOR CAPACITY IMPROVEMENTS MUST HAVE PRIORITY

It becomes obvious that anything that adds large amounts of capacity to the ATC system, or reduces the enormous implementation or operational costs, will have a large impact on controlling the future trends of the national aviation system. If this new trend is not pursued, it is possible ATC costs will become so excessive as compared with gains or benefits that aviation's growth will be stifled. At least these developments should be focused on preventing costs from continuously increasing. Some examples of possible R & D efforts aimed in this direction will be cited in this report. Furthermore, the credibility of the national ATC plan is yet to be fully established, particularly those parts of the ATCAC report that deal with increasing system capacity (where it is most urgent) at the large jetports by using multiple, parallel runways with simultaneous, closely spaced, curved IFR approaches. Here we must face the interaction of the aircraft and pilot, and the interaction of the pilot's displays with the controller's displays.

There is no guaranty in the FAA or the ATCAC plan that the 18-billion dollar ATC cost will in reality create the required additional ATC capacity and positively assure aviation's continued growth. This is true because many basic pilot-aircraft-cockpit display problems are usually outside the realm of the FAA budgets. In spite of this, validation means must be established by agencies such as NASA, so that the aircraft-pilot-display part of the system is solved, assuring that aerodynamics, handling properties, safety, runway configurations, and many human factors (involving pilots of all skills from a student pilot through a professional airline or military pilot) are not overlooked in the plan.

The complexities of a plan for a total national investment of possibly 80 billion dollars over two decades for aviation systems, exclusive of the aircraft, are such that the most advanced of system engineering concepts must be applied to the plans and their validation completed before the large implementation and operating costs are incurred. A few tens or hundreds of millions spent in the next few years for ATC validation-testing, to assure a better return on investment, can pay enormous dividends over the two decades.

If the operational costs for the next two decades, involving payrolls for perhaps 100,000 to 120,000 FAA, DOD, and other personnel, could be reduced by 10% by a better ATC system, there would be a possible 3 to 5 billion dollar savings. Consequently, system engineering and system validation must be accelerated before the major implementation plans are too far advanced. Although little can probably be done for the 1970-1975 time period, some changes could be implemented toward the end of the 1975-1980 time period that could assure lower operating costs and/or more capacity per unit of system cost during the 1980-1990 time period.

Long lead times are characteristic of new Aviation Systems. Most of the significant ATC advances are achieved with cooperative type electronic systems where all aircraft must be equipped that plan on using the cooperative ground installations. Complete specifications and standards must be available so that the airborne half of a system matches the ground half. Cooperative electronics and devices rather than non-cooperative devices are the natural and logical trend toward the solution of ATC system problems. This means more elaborate plans for R & D and implementation. The FAA normally handles the ground units, and the industry (often with DOD assistance) develops the airborne counterparts.

Simply economizing on ground facilities is not realistic if resultant high costs are incurred by airborne users of the ATC transmissions. An optimum selection of ground facilities to hold airborne costs down while providing significant capacity improvements should dominate all ATC R & D plans. Safety standards are always retained or improved. Failures of most non-cooperative plans (or equipments) for ATC emphasize the need for a better understanding of modern, fully cooperative systems. "Self-contained" (airborne-only or ground-only) collision avoidance, navigation, and landing devices impose serious ATC constraints in terminal areas and should be avoided even though they are politically attractive (since unilateral action is often possible rather than cooperative bi-lateral action). Some of these devices may serve as supplemental aids to primary systems but should not detract from increased emphasis on the basic cooperative systems.

C. NASA'S PARTICIPATION IN THE NATIONAL AVIATION SYSTEM DEVELOPMENT PROGRAM

Many of the basic questions concerning the extension of the present system, or replacement of parts of it, relate to the modern aircraft, its flight performance, and the pilots that fly it. The spectrum of aircraft types and speeds from slow VSTOL's, the single-engine CTOL, helicopters, through airline jets and supersonic fighters and transports must all be served by the nation's ATC facilities. If, for example, a few DC-3 aircraft represented the airline fleet, the VHF/ILS might suffice. However, with the jet transport--because of its flight characteristics, size, and economics--it is apparent that an entirely new ILS using microwave scanning beams must be introduced, since the VHF system cannot be "stretched" further, as it has been in the past.

Other similar examples include the density of jet traffic between major service points and in terminal areas, creating the desire to introduce direct routes, parallel tracks, etc., using Area-Nav concepts rather than a series of radials emanating from a somewhat randomly located set of polar coordinate origins. One can cite many more similar cases where the complexities of the modern aircraft, its piloting problems, the traffic control problems of serving many of them in a limited airspace require a much broader approach to total validation of selected aviation systems of various types than merely the electronics aspects only. NASA has a logical and important role to play in these validation problems, and we will identify many areas suited to NASA's experience, resources, personnel, and accomplishments.

D. AIR AND GROUND COSTS ARE ABOUT EQUAL--REQUIRING VALIDATION OF BOTH PARTS

Basically, the national aviation and ATC system is about equally divided in costs (say, about 20 billion dollars per decade in the air, avionics, avionics personnel, etc., and a similar 20 billion dollars per decade in ground facilities and services). One can examine half of the plan (mostly ground oriented) as in the FAA and ATCAC documents. However, the fragmented airborne (and user) part of the system is most difficult to analyze as to cost, safety, and utility and whether it will interface fully with the ground part. Today this is a far more complex area than a few years ago when such interfaces were nominal because the performance demands were much lower. With the potential for collisions increasing as the square of the traffic, ATC problems ten times those of the '60's will exist in the '70's, requiring much more emphasis on the interface of ATC with the aircraft and pilot.

If, for example, the cockpit were somehow fully instrumented so that the pilot could completely execute a flight track and schedule non-conflicting tracks, so that the ground merely monitored his execution of the pre-planned track and schedule, there would be little need for certain complex ground units and many personnel. On the other hand, a full "closed-loop" ATC control system from a ground central to every aircraft in flight and with instant-by-instant instructions (as in a tactical interceptor control) creates enormous burdens on the controllers, overloads communications, requires complex automatic data links, and is obviously not acceptable to our modern, well-trained pilots. There is, however, the appropriate balance (optimizing cockpit and ground control, with perhaps more emphasis than at present on giving the pilot a greater share of the track and schedule keeping than in the past) that will bring capacity up and costs down. An optimized balance of cockpit and ground control in ATC creates the best operating efficiency, safety, and lowest costs. An imbalance creates a larger total cost, shifting it to air or ground but reducing efficiency. The same high safety standards must be achieved in either case.

The success of the transponder system where the pilot input is zero while the ground controller obtains enormous amounts of information on altitude, track, identity and position--all from the coded aircraft replies--although of great value in ATC, has tipped the scales in favor of what might now be excessive emphasis on ground surveillance and close control, while minimizing this capacity in the cockpit. This concept obviously calls for tens of thousands of controllers. Area-Nav concepts with appropriate and competitive accuracies (with SSR accuracies) is the logical balance. Display of track and schedule to the pilot in the aircraft is essential if FAA controller manpower is to be balanced and not increased forever. Perhaps fore-and-aft traffic on the same track should also be a pilot-displayed function for optimizing a common track speed and aiding in spacing control using the skills of each pilot. This concept can theoretically place much of this responsibility back in the cockpit, creating a better balance of ATC functions and lower operating costs.

However, much remains in understanding pilots' complaints about ATC and in assuring their full participation in the system. NASA, with its professional engineer-pilots, simulation facilities, aircraft, airports, and understanding of the piloting problems, can operationally validate this cockpit participation and responsibility in ATC. Past experiences have indicated that too much "tactical" or "close" control from the ground has many ATC limitations. Past GCA-ILS arguments of ground control (GCA) vs cockpit control (ILS) no longer prevail, since experience has usually shown the superiority of direct pilot use of cockpit data. This trend toward more and better pilot displays of track, schedules, velocity, and track spacing is likely to prove equally significant in the terminal area where complex geometric tracks prevail. Noise abatement flight procedures as suggested in the ATCAC report are almost completely dependent on these cockpit solutions.

The understanding of the pilot and his aircraft is paramount to both types of control (close and cockpit) that must co-exist for many reasons for the next two decades. The ground controller cannot insist on performance that a pilot-aircraft-electronics combination cannot execute, nor must the pilot attempt with his improved capabilities in the cockpit to do things that are not acceptable to ATC and might be uncoordinated with the unseen traffic that surrounds him in typical, high-density IFR operations.

It is in the regions of optimum interaction of (1) the pilot and controller, (2) the ground and air displays, (3) the spacing of parallel runways with relation to aircraft controllability, (4) the allowable maneuvering for, and control of, any conflict or collision avoidance situations, and (5) the realistic low-visibility landing minimum in CAT II and III weather that the many ATC-pilot interfaces must be determined. Regulatory actions by the FAA cannot force pilot compliance, nor can pilots be expected to "engineer" the systems and displays they need for a modernized ATC system using new cockpit displays. We note an example of this in the recent Airline Pilot Safety Forum meeting where the FAA and pilots disagreed publically* on the safety and authorization criteria for CAT II (VHF-ILS) landing minima. This leaves the public and many in aviation confused, since both parties are professionally and legally responsible for safe low-visibility operations.

Many such cases of "air-ground interfaces" exist now and they will grow in any expanded ATC environment where NASA can provide the necessary resources. For future ATC we must establish the means to test and fully understand this major ATC problem of interface. Although a government agency involved in aeronautics, NASA is not burdened with the thousands of daily operating problems facing the FAA and pilots and airspace users, which usurp nearly all existing energies of the FAA merely to keep the national aviation system from failing. The DOT-ATCAC committee called the current ATC situation a "crisis;" others have called it "inadequate" and "deficient" and potentially severely constraining to aviation's growth and national value. Effectively, then, a third major ATC area exists that has not been defined adequately to date. This

* Aviation Week, August 10, 1970.

area includes operational validation prior to system implementation, fully developing the interface of the pilot and ATC system, and assuring that a balance of control in ATC exists between the cockpit and the ground ATC system. We must assure that the ATC system is actually designed and operated to serve the aircraft and pilot who are the only true "customers" for this product.

E. A FOUR-PART PLAN

Effectively, we have shown that about 20 billion dollars per decade are required for ground-oriented systems and cooperative equipments, pilot displays, etc. Perhaps 100 billion dollars of new aircraft will also be at stake. There is at present a poor interface between the two that, because of the complexities of dense traffic increasing as the square of the participants, will worsen in time. The responsibility for resolving this interface would create a major area in a national plan to overcome the ATC crisis. It is in the validation and test areas where a total national plan can be examined. For example, the FAA tends to determine what is installed on the ground for ATC that requires aircraft use, whereas the private sector and the military must follow suit with costly airborne equipments, often without any solid, quantified assurance of adequate benefits. For example, the FAA plan to extend VHF/ILS to CAT III operations required a costly updating of aircraft with multiple radar altimeters, new displays, etc. Yet, after some years of implementation the success of this plan is now doubtful for many reasons. Most of the reasons relate to the pilot, flight dynamics, and other aeronautical problems not engineered by the FAA electronic landing experts. Many of these problems could have been identified before the expenditures.

For economic and safety reasons, truly validated gains in capacity, safety, reliability, or whatever the purposes may be, must precede plans for implementation (Figure 3).

Communications are very poor between significant ATC groups, because often special interests exist, be they electronic manufacturers of the costly avionics, the ALPA, the ATC controllers, or AOPA. Each group does not within its own jurisdiction or experience hold the missing elements to a truly satisfactory national solution. A validation effort bringing these elements together would include all ATC elements and greatly improve communications and void implementation of faulty plans. The FAA, as shown in Figure 2, is primarily an operating agency with 10-year estimates of 18 billion dollars for facilities and operating personnel and about 0.6 billion dollars for R & D. It is obvious that the total national R & D effort must be increased, adding funds for test and validation ("fly before buy") prior to implementation of new facilities or systems. The past systems are so costly to operate that merely letting them "evolve" is not likely to be the solution in the future.

F. NASA-DOT RELATIONS IN ATC TECHNOLOGY

NASA and DOT-TSC have a natural interface in ATC matters, and this subject will be discussed in greater detail in Section VII. NASA is predominantly an R & D organization in aeronautics, it does not operate large aviation systems, and it has many competent facilities and personnel trained in research and validation of the many "interface" problems that exist in ATC regarding the aircraft and the pilot. NASA is a natural organization to assume in the national aviation system plan the responsibility for the interface of the ground and air elements which must be fully validated until a suitable operational "fit" is found.

This responsibility will probably entail large-scale testing and validation efforts. However, with a system that will cost every decade some 40 billion dollars to operate and modernize, affecting the future of about 250,000 aircraft costing over 100 billion dollars, it is obvious that an adequate system validation effort to assure success justifies at least 10% of the overall costs, allowing perhaps 4 billion dollars in this area over the next decade. We will detail several possibilities of a fresh, independent examination (through system synthesis and validation) of ATC systems evolving more efficiently--with more capacity and at less total national cost. These possibilities will include test and validation of new volumetric landing systems for CTOL and VSTOL, new LF/VLF wide-area systems, improved cockpit displays, airport surface control, low-cost general aviation ATC services, etc.

This environmental validation and test concept would effectively bring together the FAA, DOT-(TSC), NASA, and the DOD in examining by test and validation the interfaces between the ground and air environments--present and planned. The cost of obtaining this knowledge may be high in the form of test facilities, aircraft, laboratories and personnel, but it should remain well below the 10% figure noted previously. Attempts to minimize the cost of obtaining this knowledge ("paper" studies rather than full validation) can lead to faulty decisions. An example noted previously exists that illustrates this point. The pilots and the FAA disagree publicly on the safety of the low-visibility landing authorizations. Many technical papers clearly demonstrate the different views and reasoning on both sides of this argument. Here is a wonderful opportunity for an independent validation program, since a low-visibility landing accident involving a single 747 would cost many times what the specific validation program would cost. The flight testing of aircraft in actual low-visibility conditions, following the FAA standards, and using this data together with full simulation using a modern, new "fog chamber," electronic display-simulation, and cockpit motion simulators could shed enormous light on what is rapidly becoming a rather "hot" ATC dispute. This typifies perhaps a dozen current critical areas where the air and ground interfaces are in reasonable doubt in our ATC plans and cannot be arbitrarily determined by either party, or by FAA regulatory actions.

Furthermore, the modern aircraft with its many characteristics that adversely affect traffic control must be fully appreciated. Large physical size, wide gear, narrow runways, high approach speeds, and sluggish response are constraints on what

ATC can and cannot do. When an ATC plan requires a stream of closely spaced aircraft being fed to parallel runways spaced as little as 2,500 feet apart, aeronautics and pilot limitations predominate rather than electronics.

Noise abatement flight patterns can do more to alleviate community unrest and resentment of aviation than the long sought "quiet engine." Both vertical and horizontally curved paths are permissible in the new scanning beam ILS--strongly urged by the ATCAC; yet, no practical validation results exist that show with big jet aircraft how this can be achieved. NASA's understanding of flight dynamics and its traditional aeronautics role (originally as the NACA) can do much to assure that the ATC system, the aircraft, and pilots will actually fit each other.

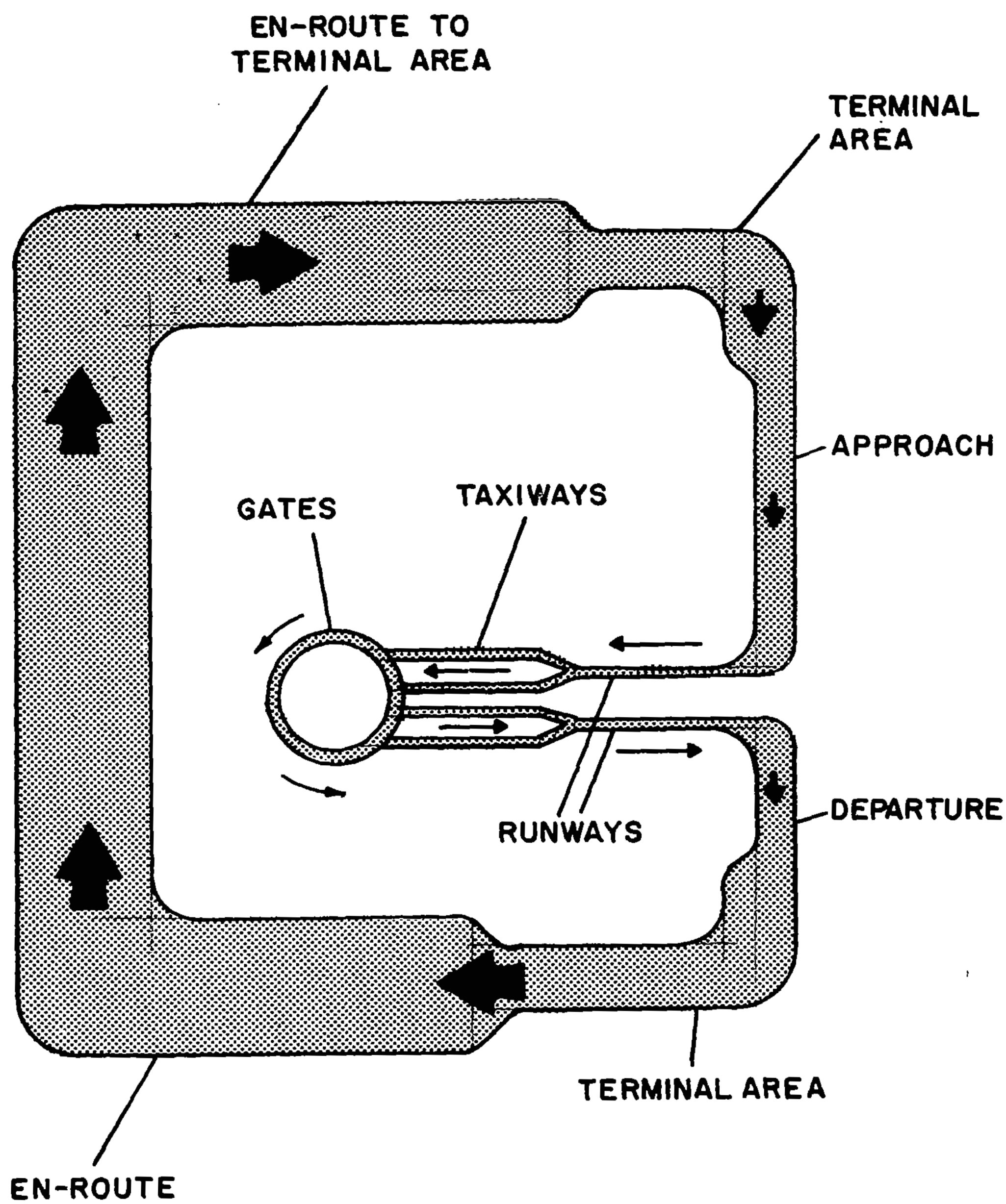
III. INTERACTING TECHNICAL AND OPERATIONAL ASPECTS OF AIR TRAFFIC TECHNOLOGY

Having presented a broader overview of the National Aviation system and the incredibly large part that ATC now plays in aviation, some of the interacting elements need description. Similarly, the nature of the interactions themselves need explanation since electronic, aeronautic, and human interfaces are so significant in ATC. Little in ATC can be considered in isolation. Nearly all elements of ATC are interdependent: where air and ground electronics must be matched, where pilot and cockpit displays must be matched, and where the optimized interface between "ground control" and "cockpit control" must be established. It is only the several technical and operational aspects, all working in concert, that will see any advances in ATC beyond what we now recognize as a limited system.

Simply adding more ground personnel, more of the same facilities, etc., is not likely to suffice over the coming critical time periods. New concepts integrated with old concepts, new systems integrated with old systems, and R & D thinking in terms of major, large increases in ATC capacity at lower costs are some of the solutions. ATC and its associated parts (exclusive of the airframe and power plants) can become so costly or so constraining that aviation growth can be stifled. Some ATC plans may price themselves out of the market, since the costs of these plans increase geometrically at certain points. Other ATC concepts exist where much greater service and capacity exists for much lower costs. Two generalized concepts will be compared.

A. <u>FLOW AND CONTROL OF AIR TRAFFIC</u>

A limited review of Air Traffic, its flow and control, will assist in defining some of the areas most urgently requiring improvements. Figure 4 shows the flow of traffic through a series of restrictions that vary at different points in the flow. A traffic flow restriction may exist because of limitations in



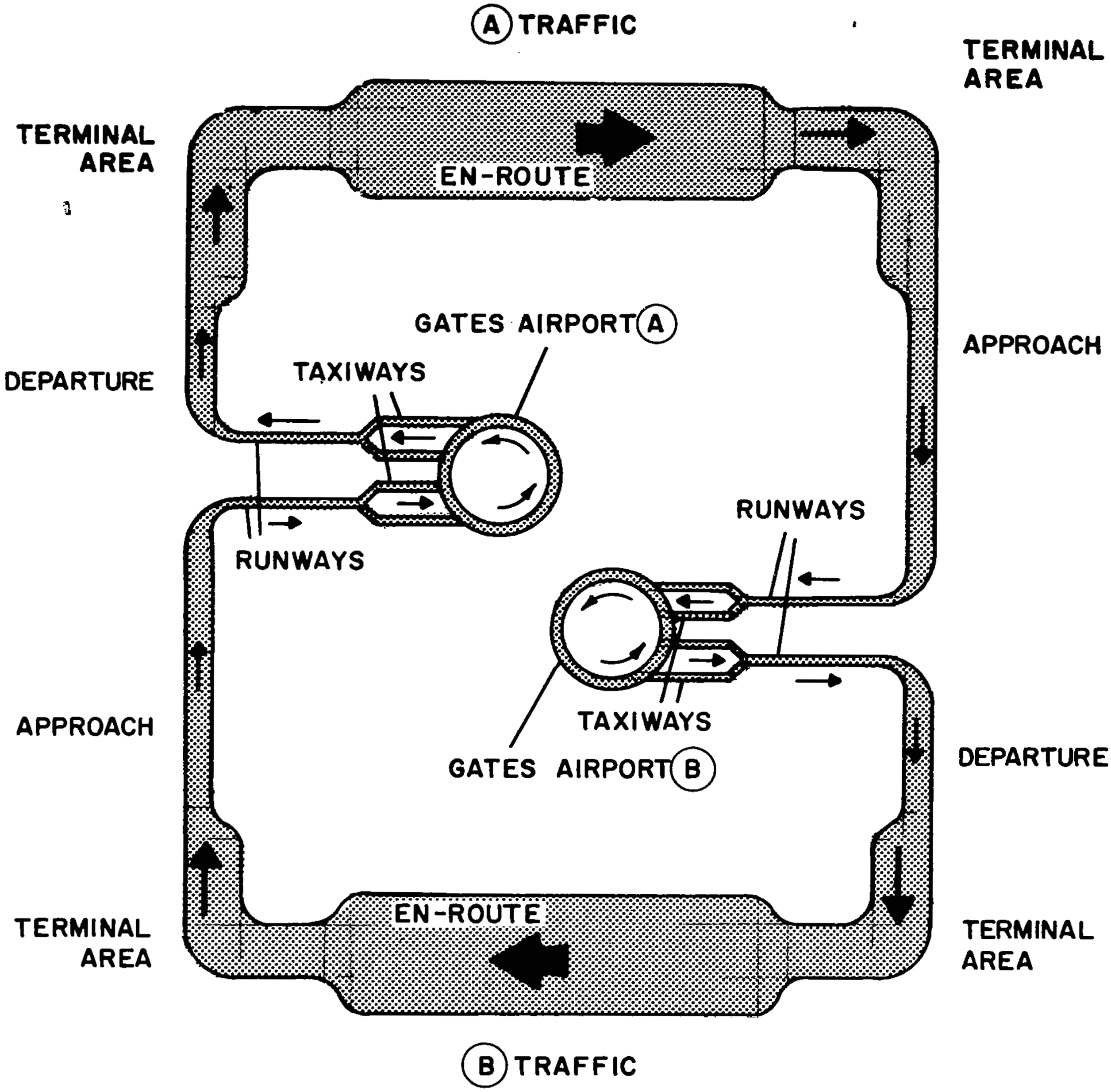
CONSTRAINTS ON AIR TRAFFIC FLOW

FIGURE 4

(1) guidance, (2) surveillance, (3) ground (controller) information, (4) cockpit (pilot) information, or (5) physical environments such as runways. For example, we note the enroute case has the largest unrestricted area, which becomes constricted when the aircraft enters the terminal area. The approach portion is further limiting to traffic flow, since a single-file operation (with adequate spacing) is required to feed the traffic to the runway. Taxiways have the potential of greater flexibility of routing than, of course, exists during the final approach, but since the velocity of the traffic during taxi times to the terminal buildings is only a small fraction of the approach and landing velocity, a large number of taxi routes is required to sustain flow off the runway. If approach speeds are 120 knots and the average taxi speed is 10 knots, the 12 times difference must be reflected in the taxiway flow capacity. New landing and surface control must be available to sustain a continuous high flow rate to the gates of modern jetports. With some airports employing a hundred or so gates, they too are often bottlenecks in the total flow analysis of aircraft traffic in a large jetport.

Since all aircraft arrive and depart a given airport in due time, the reverse flow from the gates via taxiways and takeoff runways is again a limiting factor in traffic flow. As Figure 4 shows, anything that restricts the "tubes" restricts the flow of air traffic. Queuing theory and experience show that a single constriction out of dozens of potential constrictions, can back up all traffic, causing exorbitant delays. The thinness of the connecting tubes represents the volume of traffic per unit time that can be accommodated. It is obvious, of course, that improving en route capacity will not improve the total flow if the restrictive terminal areas, final approach, and taxiway constraints remain unchanged.

To further emphasize the restrictions of current concepts of airways, approaches and surface control, Figure 5 illustrates a typical multiple, consecutive airport operation such as faced daily by airlines. Here we see the series flow of traffic



CONSTRAINTS ON AIR TRAFFIC FLOW WITH ORIGIN A/DESTINATION B
AND ORIGIN B/DESTINATION A

FIGURE 5

into and out of two independent airports. This might typify some of the popular "shuttle" services (between pairs of cities such as New York-Washington) that are now so popular with the general public. These city-pair shuttle services include New York-Boston, New York-Washington, Los Angeles-San Francisco, and New York-Chicago. Their popularity is expected to grow since they can provide transportation services requiring much less travel time than the best of any form of surface travel. Thus, the "paired" airports flow-diagram is important in many phases of aviation.

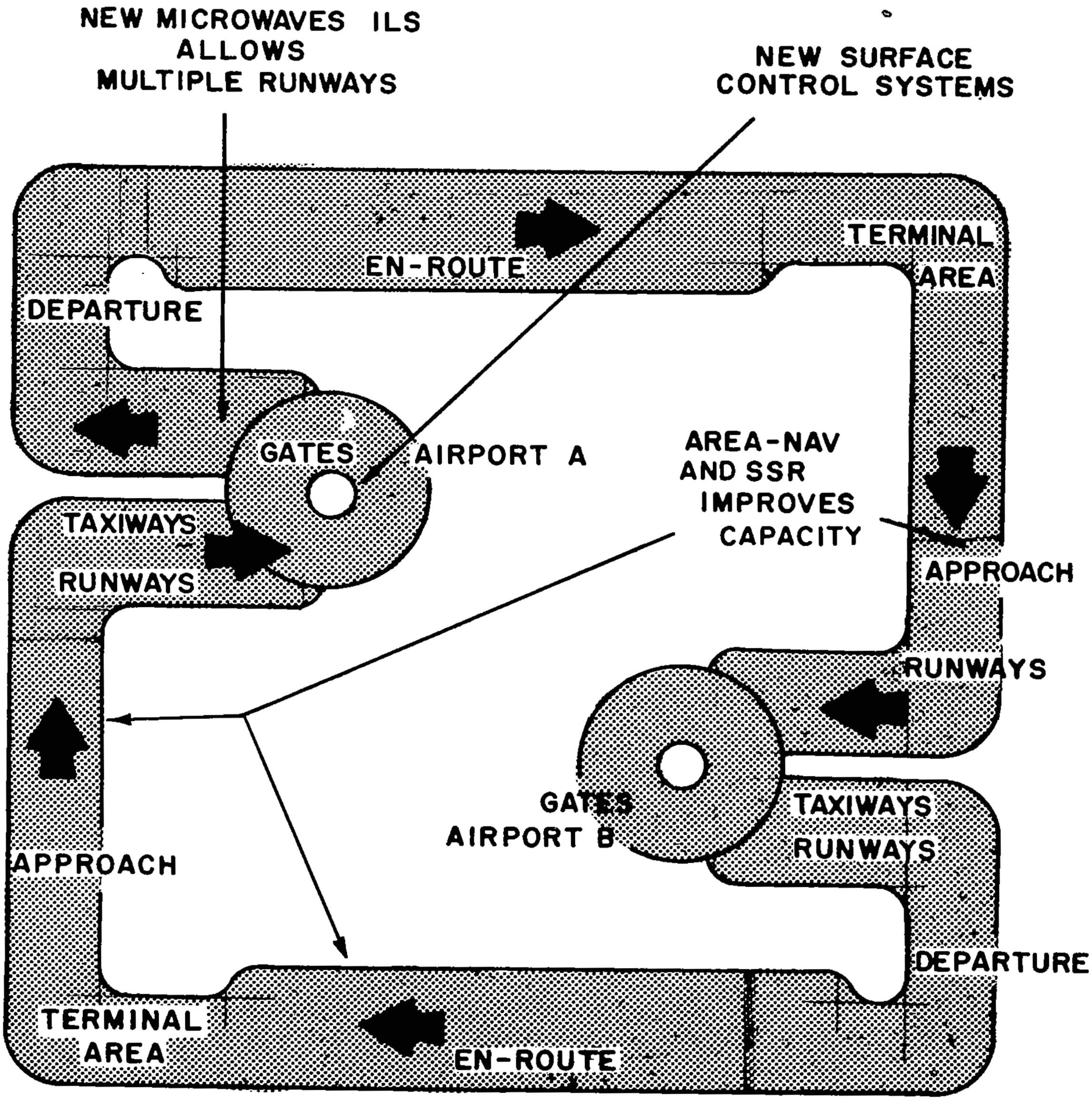
Again the probability of the flow being restricted for some reason has been doubled since now four transits of terminal areas exist, four transits of final approach, and four transits of taxiways. Anything in these twelve transits can interrupt the flow of traffic, while the potential en route tracks are sufficiently numerous as to be of minimal concern. Some interaction occurs with en route flow capacity when it is desired to enter the terminal area or depart it in a manner to optimize the track time. A dispersive terminal area track system does require a more dispersive en route system, one of the justifications for new "Area-Nav" concepts. However, even if airport A should modernize by adding more runways, taxiways and gates, the constrictions of airport B will continue to dominate and "meter" the total flow. This simple point is often overlooked when some one element in ATC is portrayed alone as making a major impact on ATC capacity.

The schematic flow of air traffic also stresses the point that all elements must be improved in concert, with emphasis going to the weakest elements if a total flow improvement is desired. Total system capacity is essentially the integrated results of the flow rates of the individual elements composing the system. By carefully examining each element, the total system capacity can often be increased by some simple methods. For example, if a "wide" Area-Nav system permitted the wide and continuous ATC coverage for general aviation and VSTOL, then wide dispersion of small airports into remote and community areas, removed from the jetports, could occur more readily. This might increase the total flow rates, since the total ATC system would now utilize many more serviceable runways that could be "fed" from ATC. We will discuss "broadcast" and "close" control concepts with respect to many of these constraints.

Emphasis should, thus, be placed on such concepts as a VLF-LF system for general aviation that hold promise of providing uniform position coordinates at all altitudes, permitting uniformly good guidance into the ten thousand (or so) general aviation airports regardless of their location. This dispersive ATC means of "wide" Area-Nav will assist in removing traffic from overloaded areas by offering adequate ATC services nearly everywhere, rather than only in highly localized areas. With greater terminal area and airport dispersion, we must bring minimum IFR-ATC capability to thousands of small aircraft and airfields that cannot be served with VORTAC's limitations. These limitations of airborne economy, ground operating costs, accuracy, coverage, or complexity of use will inhibit VORTAC's national coverage from spreading adequately. This "wide" Area-Nav concept will be discussed later.

Figure 6 illustrates the potential results of a progressive ATC R & D program wherein the constraint areas are minimized and increased in their ability to handle the traffic flow. For example, the use of a new Microwave Scanning Beam System may permit runways to be more closely spaced, increasing runway capacity; this, however, requires an electronic system for surface detection and control equipments for more rapid taxi and routing of complex traffic flows to gates. Area-Nav and improved pilot displays can increase and improve the geometry of terminal area tracks; then vertical separation is increasingly important, depending on the use of automated altitude reporting of the SSR system. Each of these systems or its modernization is a major undertaking and each new system must interface with the older units and other new systems.

The operational use must assume that all systems have had adequate operational integration and validation testing so that they work in concert with each other. Such interactions and sympathetic interfaces are often overlooked. For example, specialists tend to build only a landing system without considering the



ATC RESEARCH MUST REMOVE THE CONSTRAINTS OF TRAFFIC FLOW IN DEPARTURE, APPROACH, TERMINAL AREAS, RUNWAYS AND AIRPORT SURFACE

FIGURE 6

interface of the terminal area guidance on one side and taxi guidance on the other side. The volumetric coverage of the new microwave scanning beam system (proportional data $\pm 60°$ of the runway centerline and up to quite steep angles) allows, with precision DME, a means for computing curved approaches into runways. This widens constricted flow areas as seen by comparing Figure 5 with Figure 6. The community socio-economic interface is also realized, since curved paths will take traffic away from areas now offended by the noise that is unavoidable because of the "straight-line" limitations of current ILS (it permits only one track since it is but $\pm 3°$ wide).

Similarly, steeper, vertically segmented approaches may be used to gain further noise reductions and to elevate the jet terminal area traffic to higher altitudes. These trends would suggest a reconfiguration of the terminal airspace, in three dimensions, with slant-airways, sloping (or climb) corridors, "tunnels," etc. Some early implementation of TCA's (Terminal Control Areas) by the FAA is underway, but much remains in the technological areas before realizing efficient flow in such complex geometric configurations of this critical airspace.

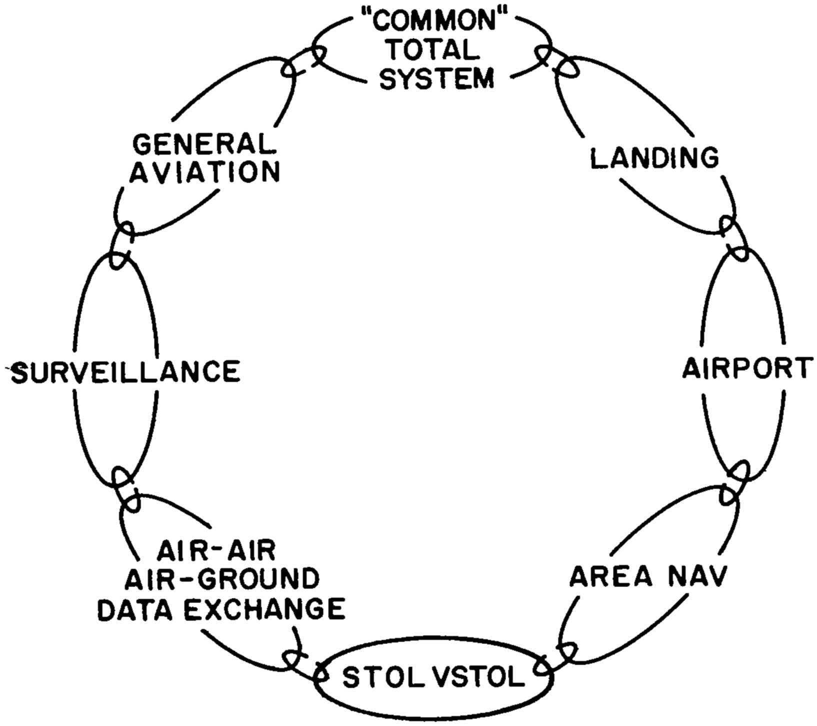
Clearly, one cannot merely add more controllers, more VOR's, and more VHF-ILS units and realize the gains shown schematically in Figures 5 and 6. Concentrated R & D is required, as is full validation before implementation. Test facilities for validation are essential since no "live" experiments with high-density areas or with new equipments and ATC concepts are likely to be accepted by the users. The coexistence programs of old ILS with the new microwave ILS is as much a problem requiring a good solution as the new ILS itself. These complex technical, political, and economic characteristics of ATC systems differ from other large national systems such as Defense and Space where centralized management and national goals permit controlled, rapid transitions or direct replacements. Patience and fortitude combined with creative thinking are required for modernization of air traffic control.

B. ELEMENTS OF A TOTAL ATC SYSTEM

Since so many subsystems, large-systems, air-systems, ground-systems, etc., make up the complete complex of a "total" national ATC system, it is helpful to attempt to symbolize its interlocking aspects. One can create various models of the ATC system for various purposes. The purpose here is to provide an overview so that a balance is maintained among the technical systems, users, and government agencies involved in ATC. We have arbitrarily divided the "total" of ATC into 8 sub-areas for further examination, as illustrated in Figure 7. Both "systems" and "concepts" are combined, since in many cases they are intermixed as, for example, in general aviation where a new concept is needed that will give a major increase in ATC services at very low costs commensurate with other ATC services as applied to airlines.

On the other hand, a technically oriented sub-area exists of "new and old" landing systems. Similarly, we have identified STOL-VSTOL for both military and civil users since the unique and valuable flight characteristics of these vehicles (compared to conventional aircraft) will have a large impact on ATC. In some VSTOL cases, new guidance and surveillance concepts will be needed; in other VSTOL cases the portability of ground guidance and control units is of great importance. The imposition of a "jet transport" solution on VSTOL ATC and landing could be fatal to VSTOL's future development. VSTOL must employ generally unused airspace and runways that do not conflict with the present users of the airspace and runways; otherwise, jet airline operations (for the sake of VSTOL) would be weakened at this stage. However, the VSTOL interface with jet operations is very important, since the movement of cargo and passengers from future major jetports to outlying VSTOL-ports seems a logical direction for aviation.

The jetports would then become major "staging" and logistic points, where passengers would be served by VSTOL nearer their outlying communities, avoiding the use of their private autos to the jetports. The "people-flow" problem of the jumbo



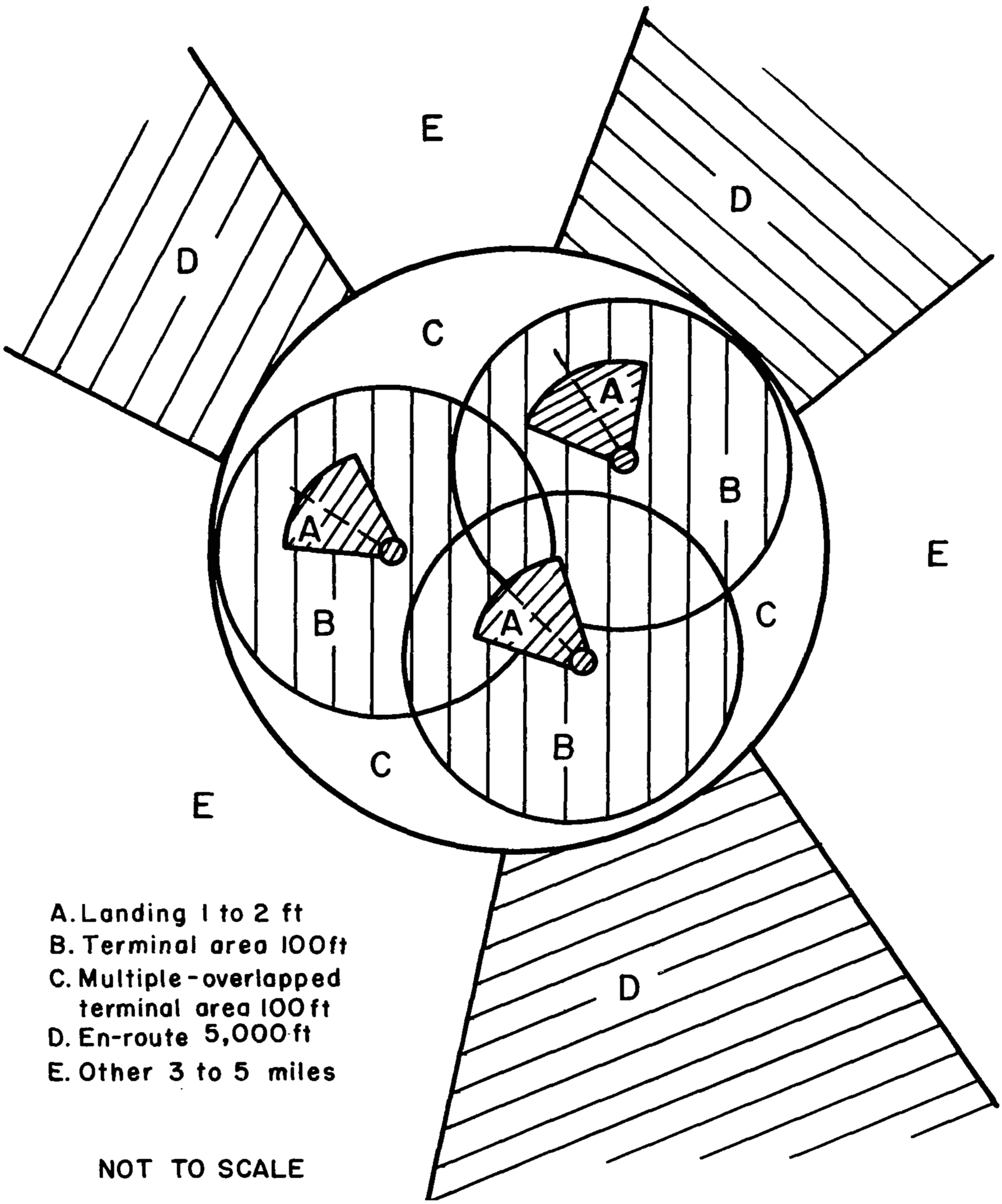
INTERLOCKING CONCEPTS AND SYSTEMS FOR ATC TECHNOLOGY R & D

FIGURE 7

jets is so serious that short-haul air transport for dispersion of the "people-flow" will be as important as dispersion of the air traffic. The necessity for many direct connections between satellite VSTOLports is also recognized in such studies as that of the CAB (N.E. Corridor), with off-loading of the jetport's traffic occurring as a valuable by-product. Again, this needs new conceptual thinking (leading to a total, national VSTOL transport system), not an isolated study of only VSTOL vehicles or only VSTOL problems; instead, the VSTOL system must be considered in concert with the continued expansion of the jet traffic (civil-military) as well as general aviation traffic. ATC is probably more critical to VSTOL's future than aerodynamics, though obviously they must be combined.

We will detail what is meant in each of the 8 areas more fully; the intent here, however, is to assign each and every ATC program (new and old) to at least one of these areas, because each program must be fitted by some harmonious means into a plan for a national total-ATC system. Too much emphasis has been given to the individual elements of a system in an isolated environment, without noting the many interfaces that must be harmoniously optimized. The message is simple: each element must be examined from the total viewpoint of ATC and no longer in isolation. Furthermore, no single element will make that much of a positive and identifiable impact on the total system, even though a single element can readily "fail" the total ATC system.

Guidance, navigation, and overall ATC accuracies vary considerably throughout the national system, and this wide spectrum of navigation accuracy is often forgotten or misused. These accuracies determine the practicality of new ATC concepts such as "broadcast" control. This fact is stressed in Figure 8 where, for example, the guidance accuracy at the threshold of a runway in CAT III should be perhaps but a foot or so vertically (and perhaps 5 feet laterally). Along an en route airway the accuracy may be a low 1 or 2 miles (say, 5,000 to 10,000 feet). The constraint on the relatively larger permissible errors along the airways (en route) may not be a serious matter to ATC capacity. Overwater



GUIDANCE AND NAVIGATIONAL ACCURACIES VS OPERATIONAL NEEDS FOR AIRCRAFT (10,000 to 1 VARIATIONS IN ACCURACY)

FIGURE 8

and international routes in low density areas may require but 3 to 10 miles of positioning accuracy. It is, therefore, up to the ATC system designer to make sure that some form of guidance and control is not inadvertently assumed to suffice when its performance may exceed or be deficient when compared with the operational needs. One example is the use of VOR "letdowns," where the descent into an airport to a given ceiling is based on flying a radial from a somewhat distant VOR station, assuming range is equivalent to time for flying to a given height at a given descent rate. This poor practice will be greatly minimized in the future with other forms of guidance as VOR let-downs have been identified as a risky operation after some accidents.

The distant off-airport VOR should no more serve as an ILS (because of its limited accuracies) than the landing system with its great accuracy in a small sector should serve as an en-route system. The wide variation in needs for guidance and control accuracies from a foot to, say, 10,000 feet (10^4) during the single flight of an aircraft demands many things from the ATC system designer as well as the users of the ATC system. Typically, surveillance systems are used to geographically overlay the guidance systems and SSR (now reaching its completion stages--about 1975) will be the major national surveillance means.

SSR data too must relate to these accuracies to adequately fulfill the function of surveillance of air traffic moving on airways and on terminal area tracks. For example, the SSR surveillance is (at present) far superior in accuracy to that provided by VORTAC, since SSR data is provided at a frequency that is about ten times higher than VOR angular data. Narrow, directive beams are used by SSR surveillance as well as wide bandwidths for accurate pulse code transmission. The SSR system used by ground controllers thus tends to overly encourage the use of surveillance and controller "vectoring," in lieu of better cockpit guidance and ATC functions suited directly to on-board pilot interpretation. Rather than having a controller or an automatic machine relay the surveillance data to the cockpit by data link, modernized navigation display and air-to-air positioning are suggested.

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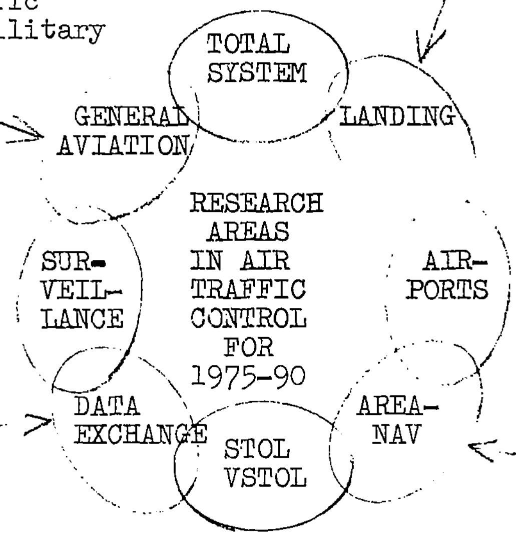
GENERAL AVIATION IFR AND ATC CAPABILITY

1. Low-cost navigation data surveillance, landing, etc.
2. Low-cost height reporting
3. Reserved low altitude airspace
4. Separate Area-Nav suited to small general aviation aircraft
5. Small airport ATC of general aviation
6. Positive general aviation/airline separation in VFR and IFR
7. Centralized control of all traffic
8. Large capacity-low cost civil-military

COMPATIBLE-NEW MICROWAVE ILS

1. SC-117 RTCA
2. Seven configurations
3. Civil-military-general aviation
4. VHF-ILS limits-flight dynamics
5. Pilot displays-handling
6. Visibility measurement and simulation
7. Low-visibility flight research
8. Test facility designs
9. Steep angle (noise abatement)
10. Landing measurements
11. Rollout, decrab, automatic course
12. Airport interface with curved approaches



AIR-AIR AND AIR-GROUND DATA EXCHANGE

1. National data link
2. National timing signal
3. Proximity warning
4. Track spacing
5. National altitude report system (air-air-ground)
6. General aviation-airlines
7. Track speed control
8. Military common with civil

AREA NAVIGATION

1. VORTAC capabilities/limits
2. Wide Area-Nav-local area
3. Omega-Loran C
4. General aviation capability
5. Pilot displays/computers
6. Satellite (C & L band)
7. ATC track assignment
8. National VLF system with integrated coordinates and timing signals
9. Military tactical-common system

SUB-ELEMENTS ASSOCIATED WITH THE EIGHT MAJOR ATC AREAS

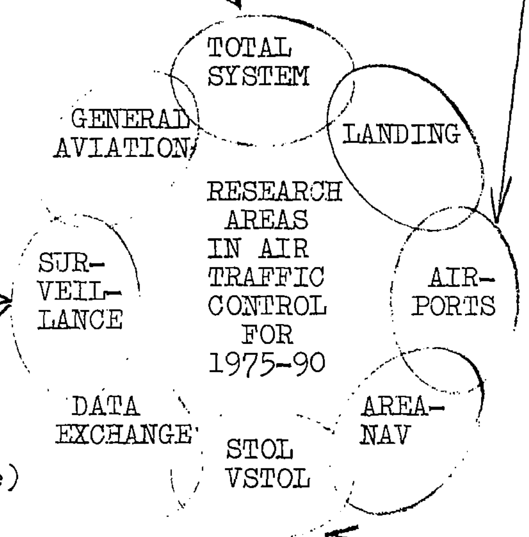
FIGURE 9A

TOTAL SYSTEM PLANNING, TESTING, VALIDATION

1. Interface of elements and agencies
2. Civil-military common solution
3. University program
4. Large-scale simulation
5. Research measuring tools
6. Live tests
7. New test center
8. Total leader-management function
9. International
10. Multi-airport terminal areas
11. Human factors

AIRPORT RESEARCH

1. Multiple parallel runways
2. Surface control of 200 aircraft
3. Surface detection and surveillance
4. Large-scale simulation
5. Runway surface, width, turnoff
6. Design for 300 operations per hour
7. Full-scale proof of concept test facility (desert floor)
8. Aircraft limitations (speed, size, braking, accelerating, etc.)



AIR TRAFFIC SURVEILLANCE

1. Advanced SSR-transponder
2. Terminal and en route
3. Airport surface
4. Primary radar (terminal en route)
5. Position reporting using data link or time-ordered signals
6. Low-cost altitude reporting
7. Small airport display
8. Computer/display of SSR
9. Optimized 4096 codes with Alpha-numerics
10. Trilateration
11. Military-common with civil

STOL VSTOL HELICOPTER IFR

1. IFR landing guidance
2. VSTOLport criteria
3. Demonstration projects
4. Noise abatement-community
5. Steep angle landing display
6. Mix in ATC with CTOL airway
7. Mix with CTOL on jetport
8. Military VSTOL

SUB-ELEMENTS ASSOCIATED WITH THE EIGHT MAJOR ATC AREAS

FIGURE 9B

We see the breakdown also of some of the technical areas such as Area-Nav where, for example, various navigational services such as VLF, LF, VORTAC, and satellites must be matched against each other and the criteria of operational usage. These criteria are often related to accuracy as is shown in Figure 8. For example, a satellite navigational system may suit aviation's trans-oceanic needs, yet it must be compared with a VLF system such as Omega, since track accuracy, positional reporting, costs, reliability, and other matters need side-by-side comparison. Precision, terminal area tracks probably cannot be adequately supplied by satellites for several reasons. It is important that in the future of ATC a balance is objectively achieved between accuracy, cost, capacity, pilot utility, reliability, etc.

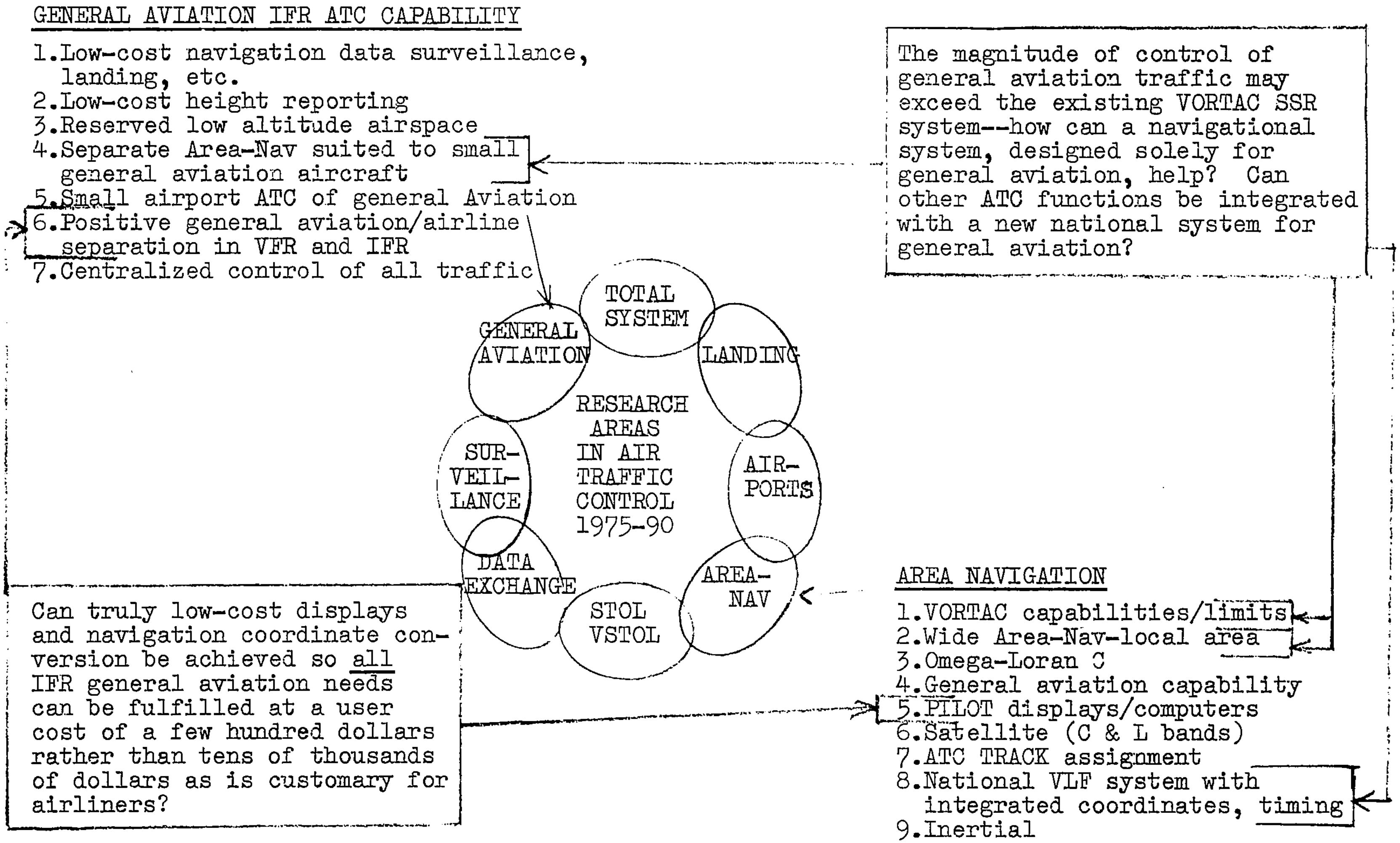
In many cases we have not given the pilot adequate instrumentation for navigation, and this area must be improved. Consequently, this pilot display aspect of ATC may eventually predominate the decision process in selecting any new ATC systems. Pilots prefer to fly solid, earth coordinates that have simple and readily usable geometric characteristics. On-board pilot displays of track flare, track longitudinal velocity, cross-track velocity, and spacing with other nearby aircraft on the same or adjacent tracks must be developed to allow the pilots equal partnership in ATC and to reduce ground controllers' overloads. Since pilots retain major responsibilities by law and regulations, more emphasis toward this pilot-oriented ATC solution will also tend to off-load the surveillance and data link areas that often are used to make up for Area-Nav and cockpit deficiencies in guidance control.

We will discuss air-to-air and air-to-ground data exchange, since this area is also receiving increased interest. The "pilot" (all pilots including the least skilled) again is the focal point with the objective of providing him essential information on ATC that can be directly applied by him in the cockpit far better than a controller or ground computer can do.

Such an "up-link" from the ground ATC computers may request specific track velocity and separation relative to other aircraft nearby on the same or adjacent track. The pilot then uses on-board means to execute the request. But a confused, telemetered picture of all ATC traffic is avoided, as is instant-by-instant instructions to the pilot. Pilots can improve the control of traffic under many conditions by optimizing the flights of their aircraft in concert with a total ATC flow plan and safe objectives. The pilots must not and cannot become ATC controllers as some collision avoidance concepts allow. It is this delicate pilot-controller-computer-display balance that must be achieved and maintained in ATC technology. Use of air-to-air and air (to and from) ground signalling must serve this concept not dominate it. The signals may be proximity signals, distance between adjacent aircraft, ATC instructions to the pilot, alpha-numerical cockpit displays, or graphic analog displays.

The purpose of this category of ATC R & D is to illuminate a significant area that needs considerable improvement. A simple, low-cost capability for general aviation and a more sophisticated capability for airlines must both be generated. The two could be two separate technologies but so utilized that each can be fully complementary with and coordinated by the centralized ground authority for ATC.

Figure 10 provides examples of the interrelationships between general aviation and Area-Nav to demonstrate by example that each of the sub-elements of the eight major areas of ATC is interrelated. This infers that the impact of wide and (dispersed) Area-Nav concepts using LF or VLF techniques that fulfill general aviation needs may be as much in the national interest as the presently planned VORTAC-Area-Nav system. The latter, though suited to high-density areas, has difficulty in other areas because the thousands of small airports are removed from the dense VORTAC ground installations since they are sited mostly on the basis of traffic demand. The VORTAC does not have low-altitude coverage nor does it serve reliably in mountainous regions below the levels of the mountain tops. VOR accuracy degrades with distance so that beyond a few miles its use as a



EXAMPLES OF INTERRELATIONSHIPS BETWEEN GENERAL AVIATION ATC AND AREA NAVIGATION

FIGURE 10

let-down type of approach facility for general aviation is highly doubtful. The uniform nature of the VLF and LF coordinates of Omega and Loran C suggest that this type of technology be used to develop an ATC service for general aviation whose coverage is at all altitudes, with superior geometrics, and with an accuracy and sensitivity that is uniform throughout hundreds of thousands of square miles of coverage, etc. Problems of electrical interference with VLF and LF are potentially offsetting to its enormous advantages. However, with modern knowledge and circuits these problems can probably be solved once enough scientific energy is directed toward the VLF-LF solutions.

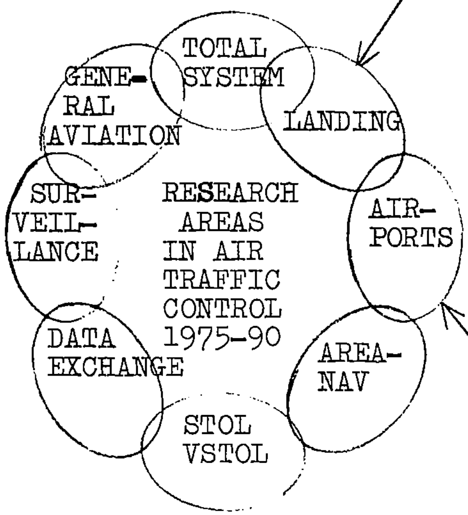
The potential gain for bringing the pilot into a more active role in ATC is emphasized for all of general aviation as well as for the airlines and the military.

The use of low-cost Area-Nav pilot displays, something readily achieved with the oblique-parallel lines of complete position (of the long baseline VLF systems), provides the pilot of a small general aviation aircraft with full positioning information equivalent to that provided by VOR, DME, and complex three-dimensional course-track computers. The low cost of VLF, and with geometrics suited to low cockpit workload with simple displays, suggests that even the private pilot would be trained to use this information upon his licensing. A study of FAA document AC 90-45, describing the complexities and limitations of VORTAC Area-Nav, confirms these views. Geographical areas that are useful and areas that are restricted to general aviation can both be depicted in simple form so that in a sense the general aviation pilot is afforded much more useful airspace than he has ever had before, since he does not have to congregate with the dense traffic to obtain the minimal ATC services that are suited to his environment. Providing ATC guidance services in his environment will lower traffic loads in predominantly airline environments.

Not only are very-low-cost pilot displays of VLF guidance superior to VORTAC displays, but their attendant high cockpit workload is avoided. By the use of the nearly rectilinear coordinates of the VLF or LF system, reporting the position of the aircraft to the low density airport, to other aircraft, or along a low density airway below the radar coverage is possible with simple tone data transmission. This latter function may come almost for "free" with adequate and creative system planning, since the coordinates of oblique-parallel systems lend themselves to this major ATC advantage. One can envision a national general aviation ATC service of navigation, position reporting, let-down, proximity signals to other aircraft, etc., all integrated, for a small fraction of VORTAC costs.

Figure 11 emphasizes another ATC (R & D) area--that is, landing and airports. The impact of, say, the new SC-117 landing system, when it becomes operational on modern jetports, can be quite pronounced. In fact, some studies suggest that the modern design of an efficient airport is now fully dependent on the evolution of such a microwave system (see the DOT/ATCAC report). In essence, the complex microwave scanning beam guidance can be as much a part of the functioning of the future jetport as the concrete in the runways and the taxiways and the terminal buildings. This thought has not really received widespread acceptance as yet, but is probably significant to any R & D in this airport capacity area, since lead times of 5 to 7 years are typical before implementation occurs.

Effectively, the ability to operate an aircraft with lower noise, more traffic capacity, at lower visibility limits, and with equal or better safety is now dependent upon understanding the relationship of a new microwave guidance and landing system to the (1) spacing of runways, (2) runway lengths and aiming points, and (3) electronic surface control. In fact, if, for example, the actual, physical siting (location) of the scanning beam radiators does not become as important a criterion in jetport design as, say, runway length, the signals may be distorted and their potential benefits seriously diminished. Taxiways improperly located in front of the vertical guidance unit can result in large aircraft standing in front of or in the vicinity of the radiating system. This would affect all radio guidance of any form to one degree or another. Narrow microwave beams, wisely used, can avoid airport



COMPATIBLE-NEW MICROWAVE ILS

1. SC-117 RTCA
2. Seven configurations
3. Civil-military-general aviation
4. VHF ILS limits-flight dynamics
5. Pilot displays-handling
6. Visibility measurements and simulation
7. Low visibility flight research
8. Test facility designs
9. Steep angle
10. Landing measurements
11. Rollout, decrab, automatic
12. Airport interface (reflections)

Ability to measure visibility quantitatively and relate it to safe, high-density operations serves ILS, surface control, and establishes surface control capability, which, in turn, establishes airspace capacity.

Determines IFR runways spacing (2,000 to 4,000 feet)

AIRPORT RESEARCH

1. Multiple parallel runways
2. Surface control of 200 aircraft
3. Surface detection and surveillance
4. Large-scale simulation
5. Runway surface, width, turnoff
6. Design for 300 operations per hour
7. Full-scale proof of concept test facility (desert floor)
8. Aircraft limitations (speed, size, braking, acceleration, etc.

Steep angle provides noise abatement and aids ATC. Is it possible with current aircraft-pilot capabilities?

AN EXAMPLE OF INTERRELATIONSHIPS BETWEEN A NEW ILS AND AIRPORT RESEARCH

FIGURE 11

disturbances that are catastrophic to VHF radiating systems. By designing the airport configuration and microwave landing system in full concert, this degradation need not happen. Obviously, scientific data must be available for this harmonious design and a "breadboard" or "test-bed" airport is suggested. Along with other national aviation test facilities, we can make a science of these ATC matters and remove the past process of intuitive decisions and "guesstimates." Similarly, the location of new, large hangars for jumbo jets can adversely affect the airport approach performance of the new ILS, particularly at wide azimuths, for curved approaches. Both hangars and guidance must be considered in new airport designs or airport expansions.

Visibility measurements along the length of instrument runways, at several points, is increasingly important if a given visibility is assured to the pilot before descending "blind" to his decision height during a landing approach in low visibility weather. The pilot cannot determine this value for himself; thus, it must be quantitatively measured, and he must be effectively guaranteed that adequate forward visibility exists for this final visual alignment where small cross-track, vertical, and heading crab-angle errors must be minimized.

For many years to come it is expected that all low-visibility landings will be radio-guided to a low descent point and then "see-to-land" is essential. The full integration of the RVR (runway visual range) data with the radio guidance data transmitted to the pilot is an obvious necessity since RVR can change rapidly, possibly becoming less than required in only a fraction of a minute. Here is an obvious interrelationship wherein the presently isolated data should be transmitted to a cockpit display of RVR, using the transmission capability of the SC-117 microwave system. RVR data measured by the transmissometers is fed to a digital scan-to-scan data transmission means using the landing beams.

C. DIFFICULTY OF ATC SYSTEM RESEARCH

Figure 12 suggests some of the problems of ATC system engineering that are unique and often not faced in other system engineering challenges. Since ATC operates 24 hours a day continuously and into the future as far as can be seen, there is little opportunity to shut it down and change over or to replace old facilities with new ones. Thus, for example, the new microwave ILS must be installed with, and co-exist on, the same runways with the old VHF/UHF-ILS for some years to come. This is true because the changeover in airborne equipments will occur very gradually, yet those adopting the new microwave airborne units will realize immediate benefits.

Not all users will want these benefits, however, and they cannot be forced to use the "new," nor denied the use of the "old." This "coexistence in ATC is a serious cost and engineering problem. Costs are higher since (1) both (old and new) systems must be maintained for some time (until the new airborne units are in widespread use), and (2) engineering of the installations is difficult because the exact same location is needed for locating the two separate radiating systems. The engineering of the installation of a microwave scanning beam azimuthal site (at the rollout end of the runway and on its centerline) must consider the fact that a large, 100-foot-long and 8 to 10 foot high VHF localizer must remain in that same location. In fact, the introduction of the new microwave equipment with its bulk and volume cannot adversely affect the VHF signals (by reflections or re-radiation); nor can the reverse occur, where the large VHF antenna may adversely affect the siting and operation of the microwave scanning beam signals.

Co-location is essential, with the microwave system "overlooking" the VHF system. This is electronically acceptable but the combined heights may increase the obstruction clearance criteria so as to force relocation of both units further from threshold to stay adequately below the obstacle-slope line. If the microwave antenna is 8 feet high on top of an 8-foot VHF

WE CANNOT REMOVE THE CURRENT SYSTEM

THE "NEW" MUST CO-EXIST WITH THE "OLD" SYSTEM

ABOUT 5 TO 10 TIMES ADDED CAPACITY IS REQUIRED (1990)

COMPLEX POLITICAL ASPECTS DOMESTICALLY AND INTERNATIONALLY

EXHAUSTED WORLD WAR II TECHNOLOGICAL LEAD

DIFFUSED FINANCIAL SUPPORT FOR R AND D

SCIENTIFIC TALENT OFTEN ATTRACTED ELSEWHERE

THE AIR VEHICLES ARE CHANGING RADICALLY (JUMBOS, VSTOL, SST)

PRIVATE SECTOR BUYS AIRCRAFT (53 BILLION DOLLARS WORTH)

GOVERNMENT SECTOR MUST SUPPLY FACILITIES AND CAPACITY

POOR COMMUNICATIONS BETWEEN DIVERSE DISCIPLINES

CONFLICTS BETWEEN MASSIVE OPERATIONAL, REGULATORY, LEGAL PROBLEMS, AND RESEARCH IN SAME AGENCY

PROBABLY THE MOST COMPLEX SYSTEMS OF OUR TIMES

PREVIOUS FAILURES IN CERTAIN AREAS

NATIONAL EMPHASIS ON OTHER TECHNOLOGY AND PROBLEMS

REASONS FOR DIFFICULTY OF ATC SYSTEM RESEARCH

FIGURE 12

localizer (such as a waveguide radiator operating at 110 MHz), then the combined height is 16 feet, which would in many cases be unacceptable at CAT II and III jetports, forcing backsetting to remain below the obstacle line.

This is but one of hundreds of examples of the engineering and design problems of modernizing any "on-line" system, but it is exceptionally severe in ATC because of safety and the physical impacts of the equipment installations on airports. It further calls for much more sophisticated R & D to envision the "coexistence" period that can ultimately lead to a major modernization of ATC by evolution and coexistence.

The rapidly changing vehicle and user demands for ATC services is also a reason why ATC research and development is difficult. One is not dealing with a standard demand. The demand is changing as to the nature of the services, as well as the quality and quantity of the services. Landing services for SST or jumbo jets are completely different from those for a DC-3 or a helicopter. The SC-117 plan is intended to have 7 or more "configurations" to cover this spectrum of aircraft and user demands. SC-117 is our first national attempt at an ATC system concept that has flexibility in services, cost, and user options (civil-military-general aviation-airlines). Airports must also be devised for optimizing VSTOL services that differ markedly from jetports

The many technical disciplines, and poor communications between pilots and engineers, between electronics and aeronautics, and between major aviation agencies further complicates ATC R & D. Each of the items listed in Figure 12 will be important, since an underestimate of the complexity and difficulty of modernizing the national ATC system will assure failure. Many do not appreciate the large range of complexities relating to what is probably our most complex system of the '70's. These parties continue to underestimate the problems and, of course, the nature of the solutions required. A real danger to aviation is to underestimate the impact of the success or failure of ATC developments on aviation's future.

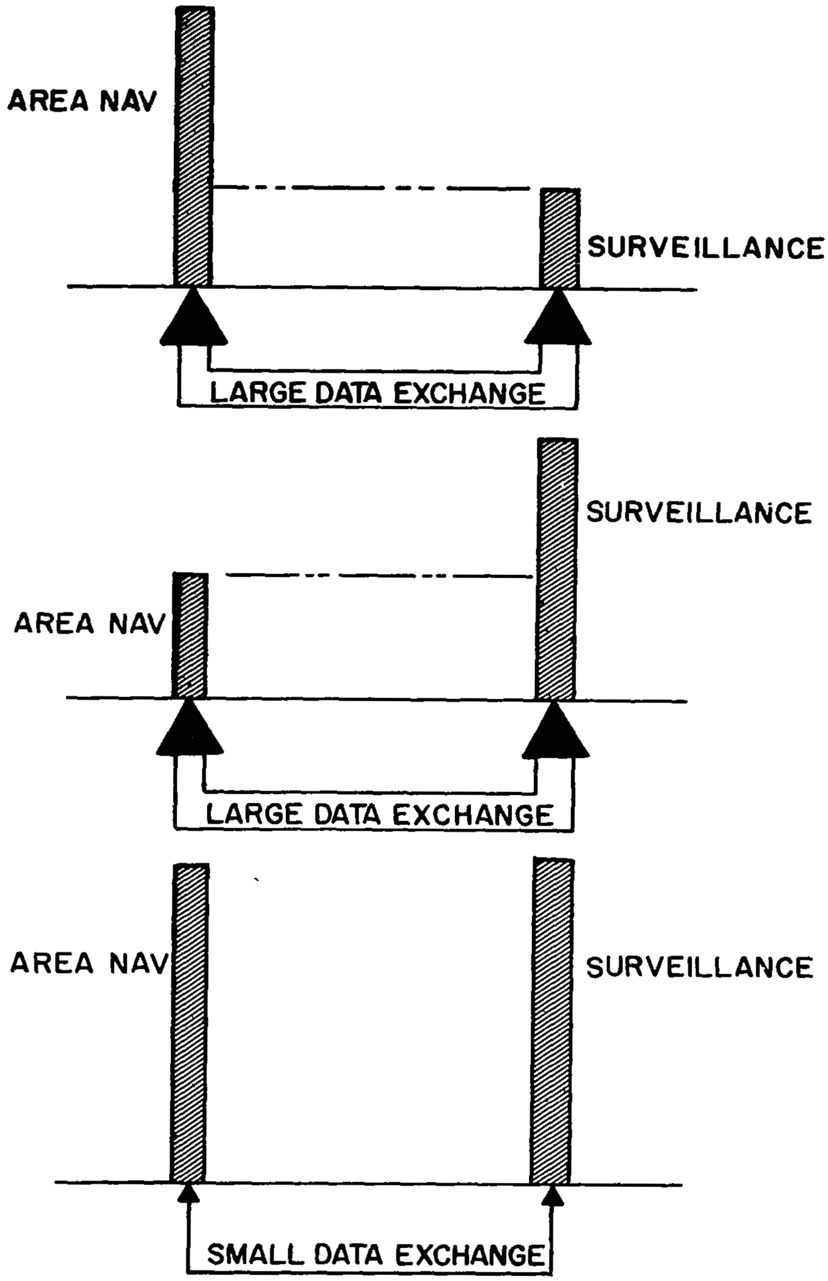
D. EXCHANGE OF DATA BETWEEN AIR AND GROUND

Figure 13 schematically illustrates an important design parameter of an ATC system: the exchange of data. Although we will devote a separate section to this subject because of its importance and impact on aeronautics, it is introduced here to fit in context with other generalized concepts. If excessive information about the aircraft exists on the ground relative to what exists in each aircraft under control, then there must be an excessive transmission of data from the ground surveillance system to the many individual aircraft. This is noted as a bar graph in the middle of Figure 13.

If, however, the ATC system is based on a theoretically perfect Area-Nav system, it allows each aircraft to affect its own ATC functions, such as maintaining (1) track, (2) "along-track" positioning, (3) track velocity, and (4) track spacing to other aircraft. The air-derived data would then be relayed to the ground control facility, and this too would be an excessive exchange of data.

If, however, the lower example is achieved where both air and ground (Area-Nav and Surveillance) are balanced and improved to complement each other, giving the pilot his needed ATC information and the controller his needed ATC information, a balance is struck and the data exchange is minimized. This is not to suggest that we want to strive only for reducing the data exchange, but to note that data exchange cannot make up for basic deficiencies that may exist. Excessive data exchange also is indicative that either the air or ground is suffering from inadequate data for ATC purposes.

As a result of the fact that the VORTAC is an old and weary system, still being modernized and updated, it will soon fall short of many desirable and essential ATC features required in an Area-Nav system with adequate capacity. This assumes that the present growth and congestion projections for aviation will hold true. Because of VORTAC's on-board weaknesses in ATC, we have relied heavily on the more recently adopted and implemented



RELATIONSHIPS OF DATA EXCHANGE WITH AREA NAVIGATION AND SURVEILLANCE REQUIREMENTS IN ATC

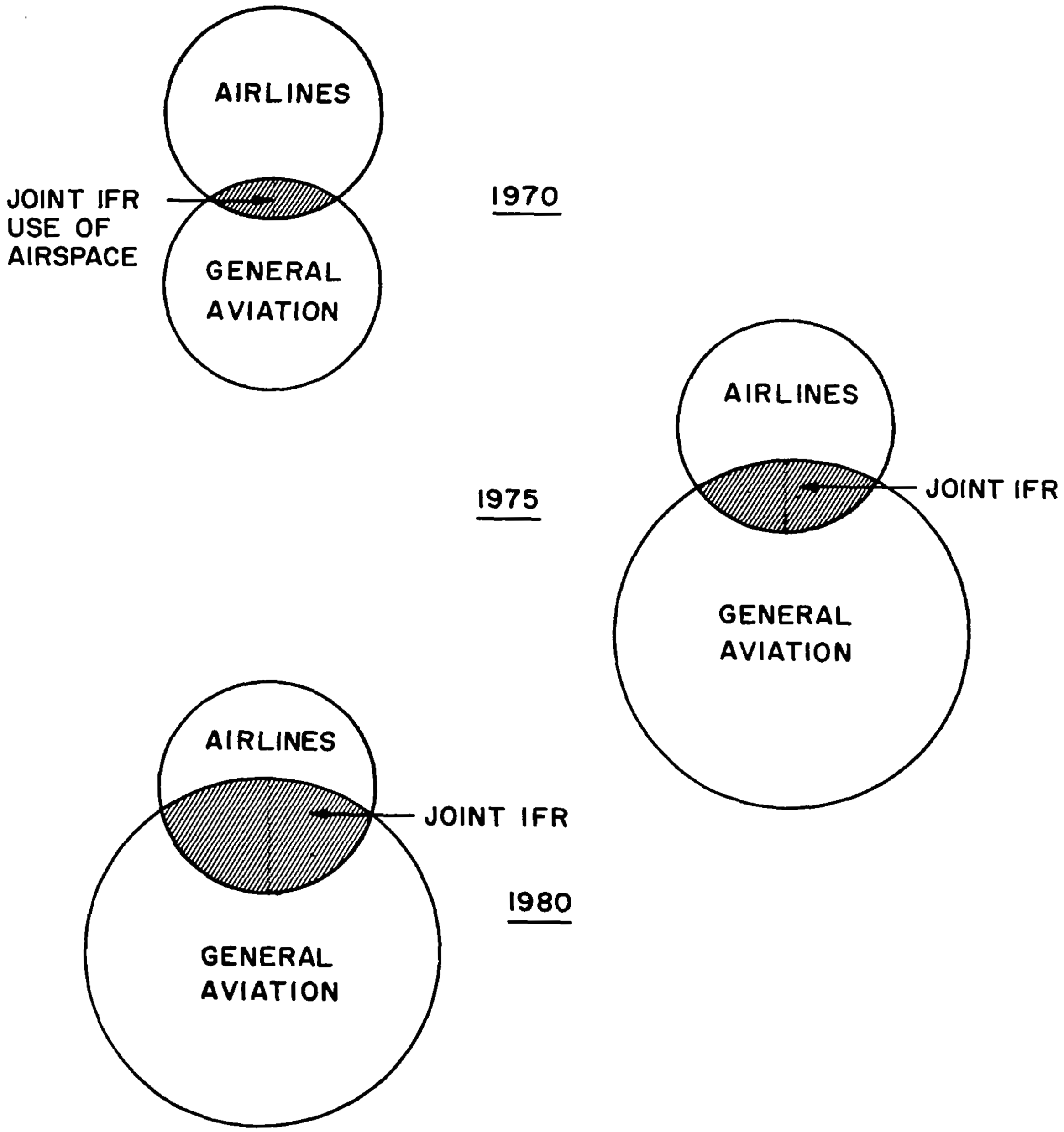
FIGURE 13

surveillance systems. The modern SSR technology and its associated signal processing has leaped ahead of VORTAC in the past few years and, as a result, surveillance or "ground-oriented" ATC predominates. SSR's greater accuracy (about ten times that of VORTAC) and the digital nature of its aircraft data transmissions have allowed vast strides in ATC automation of position, altitude, and identity data of many aircraft. SSR data has greatly enhanced ground control with digital computers and computer-driven displays of alpha-numerics.

This progress in surveillance is commendable and is essential to ATC capacity, but should now be balanced with an equally aggressive and farsighted plan for equally improved pilot information on (1) track deviation, (2) track position, (3) track velocity, and (4) air-air track spacing that matches the accuracy and utility of the controller's data. "Wide-Area" coordinate systems are most likely to achieve this goal using LF or VLF transmissions. Possibly the <u>best of Omega</u> and the <u>best of Loran-C combined</u> in a new national system would typify this new goal in ATC technology.

E. <u>TRENDS IN AVIATION GROWTH</u>

Figure 14 illustrates the trend of aviation's growth. The general aviation aircraft and pilot are becoming more capable of operating in the ATC system. The ATC transponder (SSR) has had a large influence on this change, with tens of thousands of units now operating in general aviation aircraft. The potential of a new Area-Nav system with coverage nationally suited to general aviation's needs would allow this class of airspace user to avoid dense areas as well as to optimize and expand the use of otherwise unused airspace. New, low-cost VHF communications receivers giving more channelization to general aviation, pilot display aids, DME, etc., are further adding to this general aviation ATC-IFR capability. Today's navigation and ATC services tend to make aircraft congregate in a limited airspace, while vast areas of airspace are not equally usable because adequate navigation services do not exist. New navigation concepts herein



INCREASE IN IFR CAPABILITY AND NUMBERS OF GENERAL AVIATION AIRCRAFT WILL CREATE LARGE INCREASES IN JOINT USES OF AIRSPACE, REQUIRING MAJOR ATC IMPROVEMENTS

FIGURE 14

described can overcome this ATC weakness.

The potential risk to other general aviation traffic and particularly to airline traffic increases with this development, since general aviation aircraft tend to be operated by one pilot, resulting in a very heavy workload on that single (minimum trained, general aviation) pilot, while in air transport aircraft the pilot, co-pilot and often a third officer share the load required in complying with ATC. At least when needed, the multiple crew members of an air transport can carry peak ATC workloads, while the general aviation pilot normally cannot do this. This suggests that simplification of ATC procedures, navigation, etc., is required for general aviation.

Thus, as the capability to operate in IFR or to comply with the minimum ATC requirement increases, the "mix" of airlines and general aviation in a given airspace will increase over the years. This is suggested in Figure 14 by the shaded overlapping areas. Effectively, general aviation is no longer a VFR only activity, but is rapidly changing to include IFR operations as well. This infers that if general aviation's small aircraft "mix" with airliners that are in the same or adjacent airspace, the two services must have some common denominators to assure their separation, expedition of missions, and avoidance of collisions. The engineering of new ATC facilities that are firstly designed for major capacity increases, accuracy, and low cost so that general aviation as well as others needs are fulfilled seems to be essential to the coming national aviation needs.

This does not imply that the new facilities for ATC will not aid ATC transport and DOD operations extensively, but that the criteria for selection, validation, and plans for R & D of new ATC facilities must meet these general aviation goals first and include others as well. Since it is anticipated by most analysts that the collisions will go up as the square of the total aircraft in a common ATC area, then the major increase in the shaded areas of Figure 14 will suggest that the risk will increase about 9 to 10 times over the coming decade. This is based on FAA and DOT ATCAC projections. To improve air transport (airline) safety it may be necessary to first solve general aviation's ATC problems and then base the national ATC system solution on this. Such an idea is admittedly the reverse of past history, but past history of ATC deficiencies suggests that re-ordering of priorities and future concepts is needed.

We will stress in several places in this report the impact of general aviation and the need to identify the total, national problems created by general aviation's expansion. Means to solve these problems in a few short years will be suggested.

Figure 15 summarizes possible situations that may force the creation of a national ATC plan on a broader and accelerated basis than now exists. Effectively, most of the events listed may seem alarming to some, and they are related to the increased risk now being accepted with larger aircraft, where a single accident can be of great national importance because of the hundreds of lives involved and what can be over a 100 million dollar loss.

The risk is measurable also in the national dependence on the air transport system to carry an increasingly important load that is directly related to the nation's economy. The rapid, efficient transport of people and goods has done much to contribute to new industry, new concepts of production and distribution, and to improve the general status and well being of society. Air transport has been so successful in many areas that other forms of transportation are often no longer competitive and, in fact, have been terminated, leaving large populations fully dependent on air transport rather than railroads.

The railroads are the main example of the loss of alternative modes of transportation, but shipping is a close second. The auto and bus may partially follow suit in a few years as the surface congestion is becoming extensive. To solve the nation's transportation needs of the future primarily by surface may become economically impossible since surface transportation must often displace vast real estate investments.

JUMBO JET LANDING ACCIDENTS DURING LOW VISIBILITY
(300+ FATALITIES PER ACCIDENT)

LARGE GOVERNMENT FINANCIAL LOSSES IN NUMEROUS LAW SUITS
(SUCH AS "INGHAM VS UNITED STATES")

ECONOMIC FAILURE OF AIRFRAME OR AIRLINE INDUSTRY MEMBERS

PUBLIC REFUSAL TO UTILIZE AIRLINES BECAUSE OF TRAFFIC DELAYS

INCREASE IN MID-AIR COLLISIONS

LOGICAL NATIONAL PLAN IS SOLD TO THE CONGRESS

POSSIBLE FORCES FOR CREATING A NATIONAL ATC RESEARCH PLAN

FIGURE 15

Thus, we run the risk of an increasing national dependence on air transportation for the national economic health and well being that may not be supported because of aviation's limitations caused mostly by long lead times required for modernizing or replacing airport facilities for airports and insufficient capacity of ATC systems.

The so-called ATC crisis may become an aviation crisis before we have time to modernize. This can affect major air carriers and airframe manufacturers, since if the ATC system does not allow increased numbers of aircraft to operate efficiently and profitably, they will not be operated. The public toleration of ATC delays of up to two hours reaches the point where the aviation transport system is self-defeating. Runways and major electronic supporting systems must be added to the ATC complex to alleviate this crisis.

Although mid-air collisions are rare, they attract enormous attention. Even a single-engine aircraft can bring down an airliner if they collide in mid-air. Merely perpetuating rules and regulations stating that such aircraft must avoid each other is of little value unless the technical means exist for each pilot to comply fully and readily. Low-cost, wide-area navigation in three dimensions and increased pilot training for general aviation is one solution. Proximity warning indicators (PWI) used as a part of the surveillance means in ATC will also assist. However, the prime method of collision avoidance is a better ATC system with major increases in capacity and lower costs so that all users can easily participate.

F. SERVO SYSTEM ANALOGY

The total ATC system can be considered a massive servo system with multiple controls. Each aircraft is controlled in accordance with a time-position relationship to the total flow of traffic by ATC. Each aircraft is also related to other aircraft to maintain adequate separation. It is the limits of separation that finally determine airspace capacity. Extremely high coordinate accuracy will allow the closest spacings and the best total traffic "flow" or system capacity. However, each aircraft tends to drift relative to the idealized time-position condition so that relative spacings become impaired. Because of this drift and variations in the positioning data, excessive spacing is often needed to assure that all tolerances are accounted for.

In any servo system the positioning of the object (say, a synchro shaft) is controlled by both displacement information and rate information. In fact, many servo systems use a feedback of both the displacement and rate of change of displacement, employing two sensors at the control device, such as a synchro for displacement and a rate generator for angular velocity. An optimized combination of displacement and rate results in the best performance in servo systems.

In ATC we seem to work only with displacement control data and do not utilize the powerful tool of rate data that has been accepted in other engineering circles for some 40 years or more. Before rate information was available in servo design, the "on-off" servo jittered back and forth, overshot from large displacements, and was limited in its application. With the addition of rate information, which came about because of the development of new instrumentation and circuits, servos took on a new and far more significant position in our technology.

It seems that we are now in the state of ATC technology where we have not really accepted rate information into the ATC control process. What rate data exists in ATC may only be partial or at the wrong part of the control loop. Because SSR surveillance (ground) data are about ten times superior in displacement (positioning of an aircraft) accuracy than VORTAC and its Area-Nav application, it is little wonder that what ATC rate-data is generated is generated on the ground.

However, since the ATC rate control mechanism is in the physical nature of aircraft controls such as power, flaps, speed brakes, path stretching, etc., the value of rate information only on the ground is greatly diminished in the overall, total ATC control process. Rate can be determined by the use of circuits that measure the rate of change of displacement, but if the displacement data is poor the rate-data is even worse. Thus, the use of good rate information for improving any control process is often dependent upon acceptable displacement data.

Consequently, in the ATC process the improvement of the "on-board" positioning of the aircraft with contiguous (ground-locked) constant accuracy coordinates, such as LF and VLF, provides for the first time means for obtaining cockpit rate information. The Area-Nav and airway concepts create ATC tracks; the spacing of traffic flowing on the tracks determines the total system capacity. Aeronautical restraints, such as wake turbulence, will ultimately limit spacing, but the guidance and control information of ATC should in themselves never be the limiting factors on the spacing of aircraft on a common track.

The spacing of several aircraft along the ATC tracks must be based on track-rate information to sustain the constant velocity of "group velocity" essential to both ATC criteria of high traffic flow and adequate separation between aircraft. The addition of rate data in the cockpit will complement the rate data that can be generated by the ground control system using SSR and digital computations. The application of rate information in ATC is such that it must be applied both in the air and on the ground in concert. Applying rate at only one end and not at the other of the control ATC loop will not provide the required results.

Attempts to relay ground computed rate via data link to all aircraft results in compounded complexities of addressing messages, acknowledgments, data rates, channels, sustaining dozens of such tools, and so forth. The measurement of the rate data directly with on-board sensors in terms of the on-board displacement information optimizes the solution. This does not eliminate separate rate systems, such as accelerometers and inertial units, but we want to avoid dependence on these auxiliary solutions because all aircraft should be capable of deriving the benefits of rate with simple low-cost means.

G. PILOT INFORMATION ON TRACK SPEED AND TRACK SPACING

Providing the pilot with rate information in the cockpit is an important step in any plans for increased ATC capacity. The current Area-Nav "along" airway positioning data is poor and is not used in the VORTAC Area-Nav concepts. It is this "along" airway positioning and rate of change of positioning (due only to aircraft motion) that is the ideal ATC rate that must be added to the overall ATC process to achieve a total servo system analogy of ATC. The rate feedback in the cockpit is achieved by the pilot comparing the ATC rate-control commands with measured track rates and spacing. The pilot is the only part of the ATC control loop that can affect the direct rate control required. By sensing it directly on-board the multiple aircraft on a common track and by giving on-board data to the pilot, this missing element can provide suitable coordinates and must be available for this type of on-board rate sensing.

The display of on-track spacing of "fore and aft" traffic is complementary to the on-board rate applications, since the rate is used to control the spacing of a "group-velocity" function. All aircraft in the "group" must be commanded to follow the same rate of track traversal. They each must be able to sense and utilize the common rate as is commanded for the group. The spacing sustained or commanded must be controlled by very slight changes in rate of track traversals.

These slight accelerations are too minute to sense in the SSR system in many cases and completely beyond the reach of VORTAC. Thus, if this second ATC rate function (acceleration) is to be available in the cockpit, which is the only place its functional aid (rate of change of track rate) can be applied to ATC control, then the direct sensing of the coordinates is required. "Broadcast-control" emphasizes the use of rate, separation, and track schedules of all aircraft from a common set of broadcast data and coordinates. "Close-control" emphasizes computation of rate in ground computers. Both rate computations are compatible and essential to high-capacity ATC that infers the closest of spacing along tracks into and out of terminal areas. Rate control in ATC requires better aircraft, aeronautics, pilot displays, etc., than now exist.

H. PROPOSAL FOR A NATIONAL ATC RESEARCH INSTITUTE

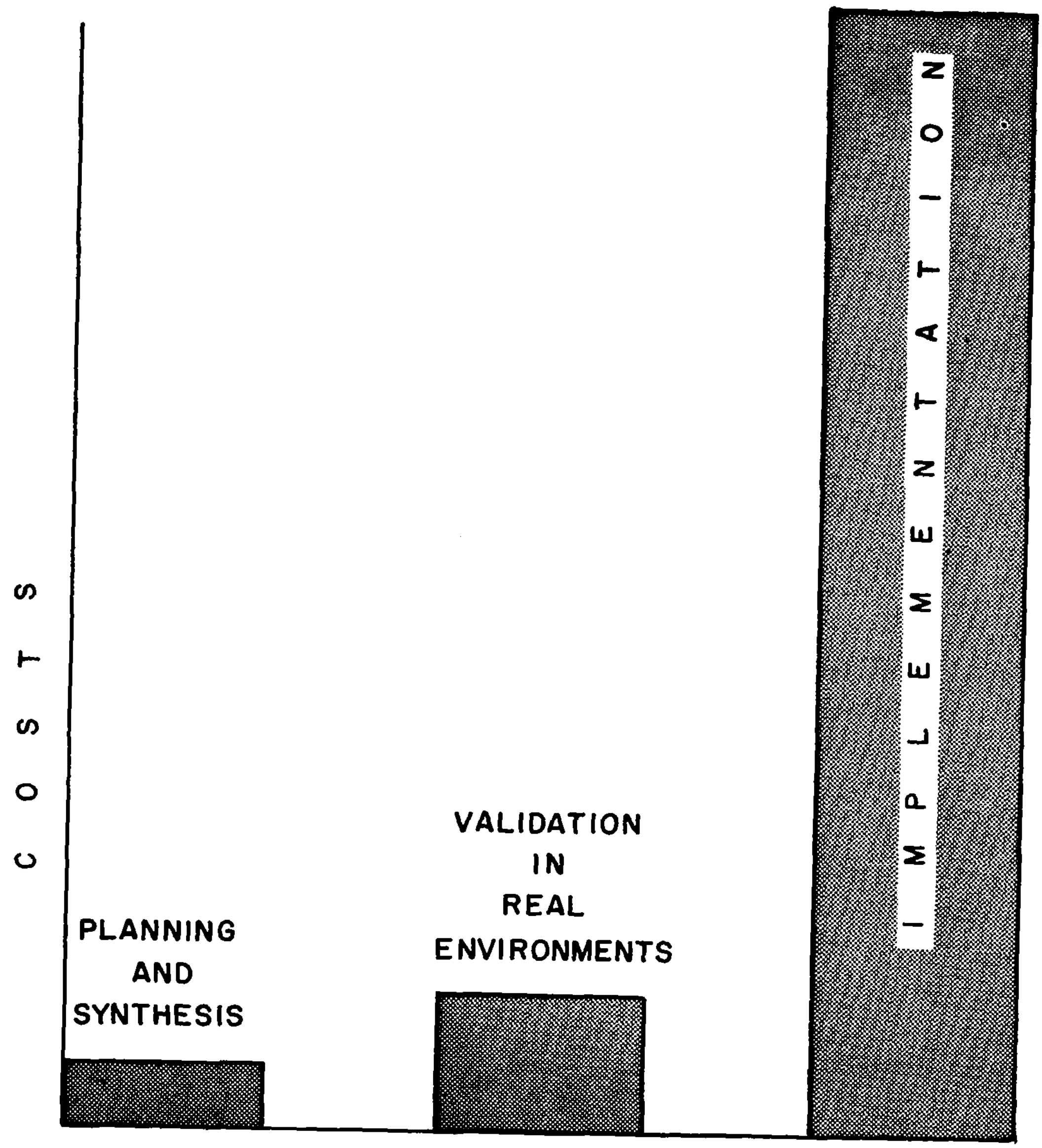
When one compares the process of law and the engineering process for deciding on a new system, one notes major differences. The law has established accepted ground rules for the adversary process in which fact-finding, open search for information, written briefs, etc., provide the information needed to arrive at opinions and decisions that guide the nation. The electronic system technologist has no such set of recognized rules, courts, or methodology by which he can foresee the means for a rational system decision that also affect the nation. To cite one of several examples, we have had some 20 new, costly, but incompatible landing system developments in the last decade. No means has existed for the national testing, adjudication, and decision process based on sets of national requirements.

Since the military operate more aircraft than the airlines and have aviation investments exceeding those of the airlines, this cannot be done unilaterally by the FAA. In fact, the FAA has not provided the much needed knowledge and raw material for these large system determinations that involve all users of the airspace including the military and general aviation. Lacking any other means, a body such as the RTCA must be used as the mechanism for making the right system decision, and this case (of a new landing system) was a voluntary approach and only those that had the inclination or the spare time could participate. Although of great value, thousands of man-hours are often spent by representatives of industry who have to market products relating to the committee's determination. These committees are nearly all "ad-hoc," there being no permanent "technological court" for system decision making involving dozens of conflicting ideas. In fact, many of the ad-hoc committees have few validation reports or quantitative data to work with. If such data is available, the committees often do not have time to study it as most members have responsibilities elsewhere.

The lawyer, for example, can start a case in a federal court that is independent of the executive and legislative bodies of the government. Similarly, a new system must be started somehow in a manner that is not solely FAA dominated, DOD dominated, NASA dominated, or perhaps based on some commercial company's narrow concepts of the national needs. Although the FAA is charged with ATC R & D, the results do not always satisfy the other agencies, the airlines, general aviation, etc. The FAA is also involved in control, regulatory, and policing functions not conducive to R & D. The FAA often appears as the inventor, the developer, the implementer, the operator, and the regulator. This does not provide any independent outside input to arrive at a balanced national plan but rather results in inbred decisions by a single agency concerning ATC and other matters.

Some means for providing a technological adjudication and validation process must be established if indeed the 5 to 10 billion dollars projected for ATC modernization are to satisfy the needs of all the users of aviation and if the ATC system is to be operated within reasonable annual costs (Figure 16). As it is now constituted an operator such as the FAA, overburdened with the daily problems of survival with the existing ATC system, cannot be charged with the massive load of new development and modernization. Possibly a new national "think-tank" devoted solely to ATC technology is needed.

The main function of the ATC "think-tank" (say, an Institute of Air Traffic Research) is to provide an objective analysis of alternatives, quantitative evaluations, etc., to the decision makers. The research institute would probably have to be independently operated to provide the climate for creative work, to pay the required salaries, and to attract a top professional staff. These are not unwarranted conditions if the caliber of effort commensurate with the "ATC-crisis" and the challenge to overcome it in a decade is to be met. The institute would



RELATIVE COSTS OF PLANNING, VALIDATION AND IMPLEMENTATION
OF NEW OR MODERNIZED ATC FACILITIES

FIGURE 16

supplement the ad-hoc activities that are now attempting to perform this function, such as RTCA, many ad-hoc government ATC committees, etc. (see a partial list of a few of their reports in Section II of this report). When such ad-hoc committees are formed or decisions are to be made, they will have some real knowledge and verified results (developed by the think-tank), not merely the extended policy of some agency upon which to judge.

Furthermore, to build a staff worthy of the profession of ATC System Technology will take time. Universities must provide new educational opportunities for students in the several aviation systems areas. New talent must be created and encouraged for many years so as to have the reservoir of knowledge to develop what is really needed in ATC. This has been done in other technical areas, particularly in defense where the Rand type corporations provide the "think-tank" inputs needed for planning and decision making in major defense technology areas.

ATC technology is now becoming a major area that deserves the support of at least one Rand type of operation. Objectivity and sustained funding are essential, because so many previous shortcomings are due to the mere extrapolation of the past or lack of sustained ATC research. A new organization for the ATC "think-tank" is suggested rather than the remodeling of an older existing organization, even though several possible candidates are available because of the reduction in needs for their services in defense. These existing organizations themselves become oriented toward military thinking, which is entirely different from what is required for ATC.

The politics, technology, economics, risk levels, international aspects, all differ in ATC as compared with defense. Consequently, the assignment of ATC research to a re-oriented defense "think-tank" is not advisable. A new organization with new concepts must be created. It must have adequate funding and assurance of at least five years of life as well as adequate salary ranges to attract from all sources the talent needed. This organization should also be responsible for assisting in accelerating the development of new talent by new university programs in ATC to provide a future staff for the ATC institute. This is not to say that several talented individuals in the military "think-tanks" do not exist who are already oriented to ATC technology. In fact, the objective should be to attract these people into the new ATC technology organization. With about 12 to 15 billion dollars required merely to operate ATC and then possibly another 5 to 10 billion dollars required to modernize it during the coming decade, certainly a "think-tank" funded at a level of several million dollars a year would save its cost many times over. Without a more scientific and objective approach than at present, billions are apt to be spent unwisely.

IV. LARGE-SCALE ATC TESTING FACILITIES

The aeronautical engineer has the luxury of testing many of his total vehicle ideas in wind tunnels. There exist today in the United States possibly 100 wind tunnels of different sizes, speeds, costs, etc. No aeronautical engineer would be expected to commit himself to a technical solution until some valid data is available. In the ATC area (any and all electronics that are used in radio guidance) there are no equivalent test facilities. Admittedly, the FAA has the FIDO (flight inspection district office) aircraft that record VORTAC signals and ILS signals, but this is not for system research, merely a means of determining whether some minimum level of performance is obtained, much as in the quality control and material testing concepts. Furthermore, a photo theodolite tracking range is available at NAFEC that can optically record the close-in operations of the aircraft testing a landing system at that airport. But, because of visibility, this service is limited to but a few miles. Tests using radar units, interferometers, etc., are not standardized nor worked out for system synthesis.

The end result is that serious research must go into methods for creating for the ATC engineer-scientist test and measurement facilities equivalent to the aeronautical engineer's wind tunnel. Similarly, several large test facilities must be constructed that are nationally dispersed so ATC system designers can use them. Avionic, ATC, and landing system designers must have the tools for their trade if they are expected to create successful results.

In this sense the ATC or avionics system engineers have never made a serious case for this instrumentation, since the entire economics of ATC (R & D) have been unrealistically suppressed in the past. Furthermore, many irresponsible technical solutions are often "sold" and later found faulty, since the only test facility is the real world. Some years ago a committee designed a collision avoidance system that was found technically to be unsatisfactory after a contract for over 600 units was awarded. In the budgeting for a new national landing facility a really good test-range facility must be added to the cost; for how are we to determine without high quality, three-dimensional measurement whether an adequate system actually exists. Even operational extensions of the current VHF/ILS are in serious doubt, since no means but actual airline usage seems to exist to validate its safety for use in lower and lower visibility conditions.

Some examples of what is intended here will help clarify this concept of measurement and test tools for conducting valid research on avionics, ATC, CAS, CAT III landing systems, etc. Only the general characteristics and objectives of the ATC research and development facilities will be discussed. In each case a study in depth is warranted in the way of a preliminary design so as to more clearly determine costs, size, location, staffing, and other more technical characteristics of the ATC test facilities. Since ATC problems will be with us for at least 20 to 30 years, the designs must consider more than the obvious, immediate problems.

A. LANDING SYSTEM PROPAGATION TEST RANGE

Briefly, a landing system propagation test range would be in a flat desert area without any obstructions for some miles. A tower about 1,000 to 1,500 feet high with elevators is utilized to automatically measure emitted three-dimensional guidance signals designed for use by landing aircraft. The signals come from landing guidance units at varying distances from the tower. Flat rail tracks are laid in several directions from the tower out to a few miles so that (flat bed carriages) the guidance system can be moved, and it can be oriented in all directions and all the three-dimensional airspace can be examined in detail. A good example is the 7 configurations of the RTCA SC-117 landing system, where several basic elements need fully controlled test data before a valid signal standard worthy of national commitment can be rationally adopted. An aircraft flies but one line in space per approach. It can cost hundreds of thousands of dollars (by flying only) to probe all the volume of a scanning beam landing system with ± 60 degree lateral proportional data, 0 to 30 degrees vertical proportional data, and precision DME to 10 miles. Several questionable areas, such as sampling rates, ground-lobing, reflections from hangars, surface aircraft, etc., are of serious concern, requiring completely controlled tests of receivers and reflecting objects to obtain data useful to a system designer. The current serious disturbances to VHF-ILS signals by landing, taxiing, lines of waiting aircraft, or over-shooting aircraft cannot be tolerated in a new landing system. The question is how can it be shown conclusively that microwaves can overcome this serious operational limitation. How does one optimize the use of many known techniques, such as beamwidths, scan integration, beam shaping, modulation, etc., testing each technique and combining techniques to reduce or eliminate the airport environmental effects?

Parallel rail tracks can convey large reflecting objects, such as large lines of multiple aircraft represented by wire mesh, as well as full-scale hangar fronts, towers, etc., thus determining by qualitative, quantitative simulations of fully controlled tests how much the guidance signal is disturbed when these objects are near or in the direct path between the landing aircraft and the guidance emitters. Both the transmission path and the objects can vary statistically or dynamically.

Such a national (landing system) test facility would be used for testing all types of landing systems, under standardized, controlled, but difficult environmental conditions realistic of modern airports, rather than on a "sterilized" runway or in wide-open areas free of reflection as is so often done today. Just as a wind tunnel cannot reproduce every aspect of actual flight, neither can this facility reproduce all environmental problems.

However, just as wind tunnels can provide enormous amounts of data and valuable results compared to aircraft design without wind tunnels, so can this facility provide much needed knowledge. Airframe replicas of 707-747's made of plywood and foil or wire mesh or old, large, military aircraft (now in desert storage) can be placed on rail cars and moved as if they were taxiing or in a lineup near the runways; thus, their influence on landing guidance signals can realistically and quantitatively be determined. A B-36 with a few added sheets of aluminum might be equivalent to a 747 or a DC-10 Jumbo jet and its full effect on beam disturbances can be studied at VHF, C-band and Ku-band. Full-scale modeling would be more realistic for simulating actual landing signals at C- and Ku-bands than attempting to use microwave scaled ranges.

ASDE (airport surface detection equipment) type radars would be used at the facility to gain more insight into airport surface surveillance problems. Similar tests would be undertaken with airborne radars (seeing-through-the-fog concepts). Tests for the quality of radar images of runways at different beamwidths, scan rates, and in raw attenuation would be conducted at this same facility. Examination of such independent landing monitor units would aid in coordinating their use with the new microwave ILS.

B. AREA-NAV TEST FACILITY

The VORTAC system also needs detailed research on limitations and growth potentials, such as data on how far angular accuracy can be developed and more understanding of the VOR "scalloping" phenomena and the use of Doppler and multilobe principles. Although VORTAC improvements have been made, the measured data is meager, and several perturbations are still unexplained. Yet, in Area-Nav the VOR-DME system must operate equally and uniformly over 360 radials (one each degree) rather than operating only on a few selected radials for "Victor Airways" that have been optimized. This change in VOR usage from a few radials to all radials, using an airborne computer for track determination and separation from other aircraft with similar computers, forces the acceptance of new standards of accuracy, probability of course-shifts, multipath reflections, scalloping, vertical coverage, etc., never contemplated by the original VOR design. Even the principles of reflections and multipath transmission are not fully understood after 30 years of usage. Similarly, the DME, although better in some respects, has many propagation problems (such as vertical lobing, for example). This facility would use precision methods of position determinations, controlled means of space measurement (high towers at many azimuths) and the ability to inject multipath reflections for testing. It is essential to create a new concept for a facility for scientifically measuring the "signals-in-space" of Area-Nav devices such as VORTAC, Loran C, and Omega.

C. AIRPORT RESEARCH FACILITY

The main objective of an airport research facility is to determine what surface elements are best suited to increase the capacity of major jetports under all conditions including low-visibility operations. Computer simulation is a major first step, but can go only so far and, at some stage, the actual testing with a full-scale "flexible airport" is essential. Flat desert areas exist --like those near Edwards AFB (NASA Flight Research Center)--where runways can be marked on the desert floor using dye or oil markings so that a full-scale jetport can be laid out. Electronic testing (such as magnetic loops, infrared, Doppler, radar, photocells, etc.) of devices for the detection of aircraft and vehicle movement through hundreds of intersections is a little-developed science that is now becoming a priority item at some major jetports.

The ability to scientifically determine how to operate parallel runways in the closest possible proximity must be determined, as vast amounts of costly real estate exist on current airports that could be used to increase capacity, if only the technical data existed on close and IFR runway spacing, turn-offs, etc. Much of this can be simulated in computers, but some real-time and real-magnitude experience is needed. The only method used today is to build many of these facilities as actual operating airports and only then to realize design deficiencies. Changes in environments (aircraft size, mix, peak hours) make modification to existing airport designs necessary, but no means now exist to physically test the changes before committing enormous sums of money and inconveniencing thousands of flights. This is another area in ATC that has received limited scientific attention, resulting in a random costly process of design by cut and try methods. For example, only two of JFK's original six runways are in use today, and major changes to JFK's configuration being proposed cannot be fully assessed; thus, the probability of successfully meeting certain objectives is not known before construction begins costing hundreds of millions of dollars.

Such problems would be investigated using full-scale simulation on the desert floor without the cost of laying runways. Similarly, electronic surface detectors, surveillance radars, cable guidance, intersection signals and electronic controllers would also be investigated in full-scale environments. This major test facility will go a long way to assure the successful future of many large-scale civil jetports costing 500 to 800 million dollars each. The reason for emphasizing this test facility is that the surface of the nation's airports is probably more nearly saturated and overloaded than any other individual element of the total ATC system. Since each aircraft must traverse the airport surface environment twice on each flight, this can be the most constraining feature to any future traffic growth if validated means for major surface capacity increases are not quickly found.

The use of up to four parallel runways to add operational capacity is theoretically interesting, but it has many problems because of the interaction between runways, the need to cross active runways, etc. To develop new airport theory and testing it by actually building airports at a cost of hundreds of millions of dollars each is simply poor scientific planning. Computer simulation can be very important but, to use only computer simulation leaves too many doubts and can be misleading.

Various airport design techniques using simulation, computer graphics, etc., must be complemented by some real, full-scale, high-capacity airport test work. The possible use of small motorized vehicles that can pull outmoded, large aircraft (now in storage) at the right speeds and quantities to create actual surface movements is a means to accomplish this. Obviously, a detail design of such a major test facility must take place first. The electronic detection, central surface control, electronic surveillance means, cable guidance, data signalling, etc., would work against real targets and produce real results in the application of the test airport. With flexibility in geometrics and size of design on the desert floor, and complete control of surface traffic, factors that cannot be determined at an actual "live" working airport can now be investigated. Many nationally significant problems can thus be solved at lower costs. This is a fundamental input to future ATC, because we are now contemplating the possibility that at a super jetport of the future 400 to 500 movements may occur per hour, feeding some 300 gates.

One very obvious design criterion that must be answered is the cross-wind characteristics of the new airliners expected to be acquired in the next 12 years. If they can tolerate cross winds of a given amount, then cross-wind runways are unnecessary. If not, cross-wind runway capability is necessary with its enormous impact on cost and capacity. This fundamental issue in airport design has never been really faced by the aeronautical engineer in answering inquiries of the airport noise abatement and radio guidance engineer. Guidelines on cross-wind operation must soon be established for at least the next decade as real estate, taxiways, number of landing systems, noise abatement, etc., hinge on this factor. If cross-wind conditions of 35 to 40 knots can be safely tolerated, it has been estimated that cross-wind runway needs would be dropped to only 1 to 2 percent. However, this is a major "if" whose erroneous solution would rapidly worsen the nation's airport and safety problems.

It is likely that such a large cross-wind component will not be tolerable and that cross-wind runways must therefore be used. This requires a design that allows rapid shifts in operations between runways, something that now causes serious delays. Wingtip vortices are obviously involved throughout; this is an airport problem that could be fully researched in full scale at the proposed facility. Such vortices might eliminate close spacing or the use of STOL aircraft and helicopters at jetports unless the "mix" can be safely achieved. Contamination of air by unseen high-velocity turbulence is as much an airport research project as is magnetic cable design, but it must be examined in a broad context. A national Airport Research Facility could start to provide this needed data.

D. LARGE-SCALE FOG CHAMBER TESTS OF LOW-VISIBILITY LANDING

The nation still owns a few very large dirigible hangars from the days of lighter-than-air vehicles. These large hangars are now not used at all or used only at very low utilization rates. The University of California, under Professor Horonjeff, built and tested a limited "fog chamber" some years back that added much to our knowledge of runway lighting for instrument landing. Since this chamber was a "first" and was built with a relatively low budget, it has certain obvious limitations; for example, it is not possible to maneuver longitudinally, laterally, vertically, but merely to move on a single sloping track in a narrow chamber that is about 800 feet long.

By utilizing the large volume of space inside existing dirigible hangars and creating finely controlled visibility with water vapor (as Horonjeff has done), it is possible that the effect of nearly free maneuvering flight can be realized. This type of arrangement will be far more realistic than a TV screen or a runway model, because wide-angle, fully articulated, visual cues (brightness, contrast, visual alignment, etc.) can be created. The height of some of these hangars seems adequate or could be increased at one end so that a scale factor approaching 2:1, or at worst 3:1, could be realized. The results obtained would be far superior to those realized with the original small fog chamber. The maneuvering trajectories of the cab would be activated by an equivalence of ILS beams and pilot displays as they now exist. Included in the design of the fog chamber is the ability to create different runways with the hundreds of lights that are now required (approach, strobes, cross-bar, threshold, centerline, VASI, narrow gauge, high speed, turnoffs, perimeter, colors, etc.). Full three-dimension, lateral movement of the cab (within $\pm 3°$ of full-scale ILS) and full freedom of cab attitude can be created by placing the cab on a large motorized dolly with hydraulic lifts. The Ames Laboratory two-dimensional, cockpit translation track is typical. A modified, large-scale "cherry picker" used by most electrical power companies might move the cockpit cab in three dimensions allowing three axes of rotation by using gimbal mounts.

The creating of pitch errors in the see-to-land part of the landing maneuver is considered by many as a high risk item, and "heads-up" displays (HUD) or independent landing monitors (ILM) have been promoted by many manufacturers at great cost. Yet, we do not know how these will work in the "real" low-visibility world with such variables as ILS aiming points (differing at each airport), dramatic visual illusions that force the pilot to disbelieve some part of his sensory inputs, and the fact that slant range visibility is never the same as runway visibility range, the only information now provided the pilot. All these displays must serve the new microwave ILS system and lights must complement and supplement, not usurp or confuse the basic ILS functions. Fog chamber simulation will optimize this relationship. Slant range measurement tests may be possible with this advanced fog chamber.

This step beyond the creative initial efforts of Professor Horonjeff could at this time in the history of aviation (wherein nearly blind landings are actually being attempted with increased but unknown risk levels) offer much to validate many psychological, non-machine, and radio guidance interfaces never attempted before. In this type of setup, the free maneuvering movement of the pilot in his cab could be realized over perhaps a simulated trajectory with visual cues of between 2,000 and 4,000 feet in dimension. Visual data (as restricted in fog) could not be introduced for different heights over wide azimuthal changes so that pitch, roll, yaw, speed, vertical, lateral, and range errors on ILS can be simulated and all elements evaluated in a full-scale simulation.

The new fog chamber could also provide STOL/VSTOL and helicopter low-visibility tests at reasonable costs. Since steep angles (5 to 15 degrees) are involved, less area is needed and the same fog chamber will suffice. Little is known about visual cues in steep approaches with slow but highly maneuverable aircraft. The VSTOL landing problem differs markedly from the jet fighter or transport landing problem. One cannot apply jet landing parameters and concepts to VSTOL. The fog chambers would be suited to solving both problems. Such facilities would add much to the nation's knowledge about this critical problem for a range of aircraft. Lakehurst, Ames (Moffet Field), and possibly one or two other locations have such dirigible hangars, and two or three of them could be converted for this major national test facility. A study of these facilities should be undertaken to optimize them for use as fog chambers for CTOL and VSTOL.

Critical areas that could be investigated with this modern, large, flexible fog chamber are:

1. Pilot visual cues of various lighting configurations under varying RVR and SVR conditions. [Presently, in the narrow small chamber, tracks limit side step, duck under, and variable glide path intercept point (GPIP); all these factors are known to create visual problems that exist in various forms in modern jet low-visibility landing.]
2. Testing of Heads-Up Displays (HUD) in a far more controlled low-visibility environment than is possible in a jet transport that costs several thousand dollars per hour; thus, the known visual alignment problems of HUD, ILS localizer, ILS glide path, GPIP and other "instrument-to-visual" referencing cues can be fully tested (see CR-1188 for some further details).

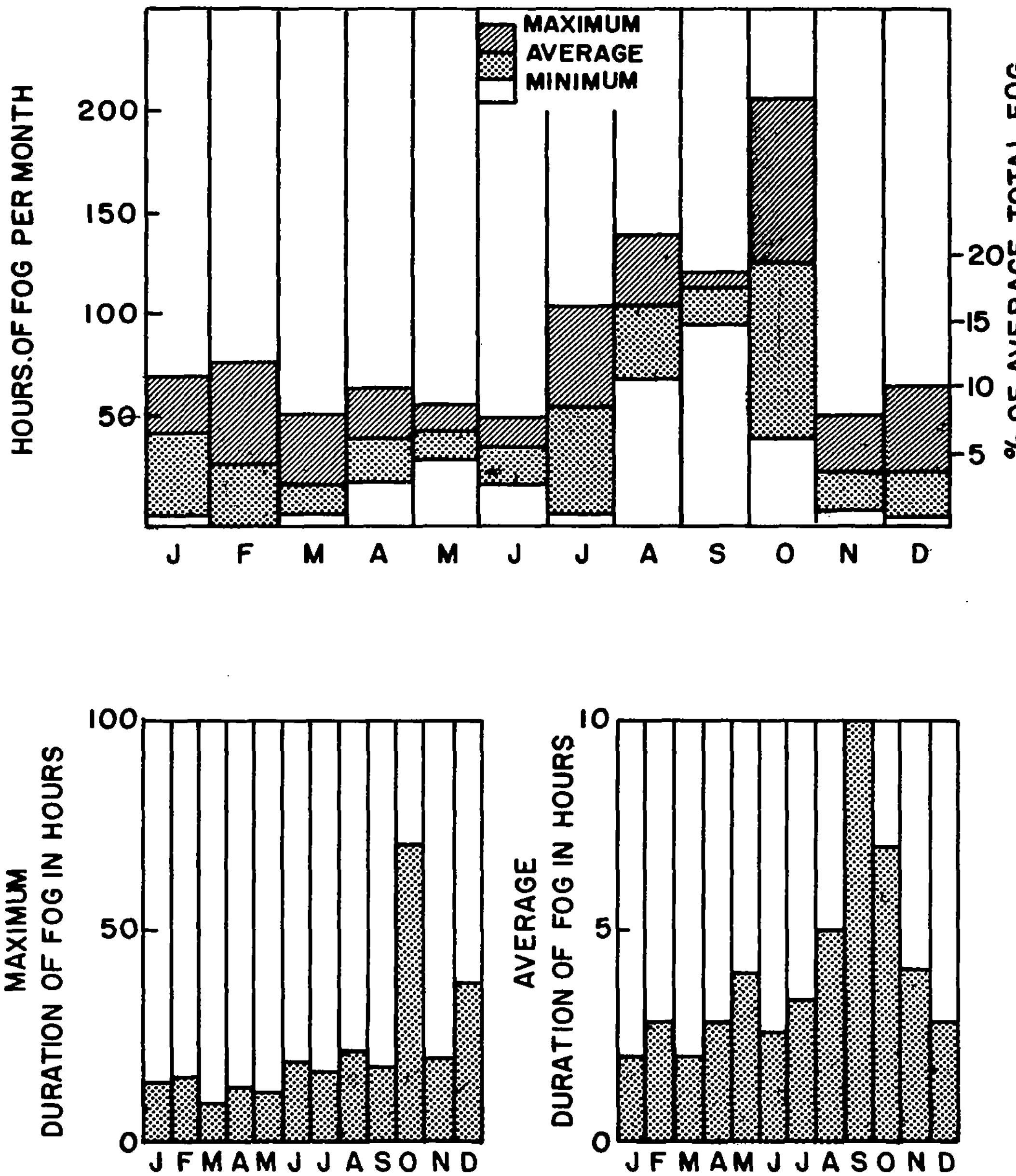
3. Testing of the rollout guidance provided by centerline lights and turn-off lights in high cockpits (up to 50 feet) when maneuvering off a runway (by properly scaling the pilot's eyes for simulation of the right elevation above the simulated runway). High-speed low-visibility rollout in cross winds with beambends can create believable illusions. One illusion created by a curved line of high-speed turnoff lights was that the aircraft was veering or yawing in a cross wind and resulted in a serious accident.
4. Experiment with the "see-to-land" concept in more depth with crew drills (who is heads-down? who is heads-up? etc.) and the guidance transition from radio (flight directors or autoflight) to the visual "see-to-land" in 1,200, 700, and 150 feet of visibility.
5. Visual landing aborts (missed approaches) in such low visibility conditions are risky and can be treated in the fog chamber, since it is likely that the length of the large chamber could accommodate this maneuver by possibly having a parallel system folding back. The pilot is blacked out visually for a couple of seconds as he is placed into an abort from high speed rollout.
6. A simulated, direct, positive control of flare guidance by radio could be accomplished while the visual lighting cues are in the 700 to 1,200 foot visibility range. This has never been done previously, and it is possible that a serious false pitch illusion exists; in fact, this has been suspected in some accidents. Consequently, in such a low RVR, the flare will have to be actuated before adequate visual cues of the approach or terminal aiming points are in sight--something few pilots have ever experienced. Much must be learned as to how this can be done. Many "velocity-vectors" are apparently used subconsciously by the pilot.
7. The testing of runway visual traffic signals, such as stop-go signals at intersections, visual velocity signals, turnoffs, surface-routing messages, visual data board messages from tower to pilot, etc. (all in the low visibilities created

in the fog chamber) again require wide maneuvering limits and wide-angle cockpit vision not now possible in the existing narrow fog chamber.

E. TEST FACILITIES FOR ACTUAL MEASUREMENT OF LOW-VISIBILITY LANDINGS

Although it may seem that undue emphasis is being placed on low-visibility landing, it must be remembered that not only is the risk in this operation perhaps a hundred times as high (for, say, CAT III) as for normal en route flying, but that past statistics point up this area as the one where the greatest fatalities and losses occur. Economics and noise abatement are also closely related to landing operations. Consequently, the risk level for advanced concepts of lower and lower visibility operations must be completely quantified and validated, since little is known about such factors as approach-aim point, threshold-height, flare-point, bleed-off speed, etc. It is likely that the current ILS path criteria are poorly suited to the flight characteristics of modern jet aircraft and particularly the new, large-bodied aircraft.

Although the fog chamber facility, which is also noted as a needed addition, will prove valuable, there must be feedback to actual operational results as the visibility authorizations are lowered in accordance with current and future regulations. In fact, a national facility for flight testing in actual fog conditions with actual large jets should be established. For example, the airport at Arcata, California, has been used for many years by the Bureau of Standards for research work with transmissometers, since low visibility and fog is so prevalent there throughout the year. Since a great deal of historic and weather pattern data exists at this airport (see Figure 17 and Table II), and it has been previously identified and used as an excellent location for actual testing of "fog-landings," no better (U.S.) airport is likely to be found. Its traffic is low so that an R & D flight program would not conflict with public use of the airport. Modern airline and MATS aircraft should be used



(Source: Mr. C.A. Douglas, National Bureau of Standards)

FOG OCCURRENCE AND DURATION BY MONTHS
AT ARCATA-EUREKA AIRPORT

FIGURE 17

TABLE II

SUMMARY OF METEOROLOGICAL OBSERVATIONS
NOVEMBER 1962-OCTOBER 1963
ARCATA-EUREKA AIRPORT

Month		Ceiling: Number of occurrences of ceilings less than					Visibility: Number of occurrences of visibilities less than					Minima: Number of occurrences with conditions below		
		100'	200'	300'	500'	800'	¼ mile	½ mile	1 mile	2 miles	3 miles	200' or ½ mile	500' or 2 miles	800' or 3 miles
11-62	hours	17	36	68	105	124	29	44	95	114	138	43	130	154
	days	5	8	11	13	17	7	8	12	13	15	8	14	18
12-62	hours	84	111	140	159	170	98	121	183	190	217	124	206	226
	days	12	12	14	14	17	13	13	15	16	19	13	16	20
1-63	hours	12	14	19	26	51	16	20	30	46	66	20	46	75
	days	4	5	7	8	12	5	6	7	11	12	6	11	13
2-63	hours	8	14	20	41	68	14	18	28	57	68	18	66	89
	days	3	5	9	12	17	7	7	11	14	15	7	14	20
3-63	hours	-	-	1	13	41	-	1	2	9	29	1	16	44
	days	-	-	1	3	6	-	1	3	4	6	1	6	7
4-63	hours	-	2	5	10	28	-	2	4	12	17	2	14	32
	days	-	1	1	1	7	-	1	1	3	4	1	3	8
5-63	hours	10	18	31	75	134	11	18	40	58	78	19	80	141
	days	2	4	6	10	15	2	4	7	8	12	4	11	16
6-63	hours	12	22	46	100	154	14	26	52	76	99	27	106	160
	days	4	9	11	14	21	6	11	12	13	13	11	15	21
7-63	hours	12	16	26	71	131	12	16	33	55	84	16	80	144
	days	4	5	6	13	21	4	5	8	12	17	5	13	23
8-63	hours	26	59	124	220	355	28	60	129	200	248	62	242	370
	days	11	17	23	23	27	13	17	22	23	24	18	23	27
9-63	hours	68	108	151	214	285	68	95	148	201	235	110	227	296
	days	14	16	18	23	25	13	15	18	22	23	16	23	25
10-63	hours	16	22	41	60	93	12	22	36	60	76	23	74	102
	days	3	4	8	12	12	2	6	8	9	12	6	13	14
Total	Hours	265	422	732	1104	1634	302	443	780	1078	1355	465	1287	1833
Total	Days	62	86	115	146	197	72	94	124	148	172	96	160	212

for this purpose, since many of the problems are related to this type of large jet equipment, their flight parameters, the pilot, his instruments, and the regulatory matters pertaining to runway visibility, slant visibility, and visual landing cues. In essence, we would expose test aircraft and test pilots to the lower regions of low visibility, rather than the public as now planned. All testing would be under fully controlled conditions and would include measurements of visibility at many points, radio guidance data, recording of actual aircraft position and attitudes, etc., so that fully quantified data exist.

Some 20 parameters define a successful landing. These parameters have been identified and developed to the stage that they can be quantified and then related to the probably success or failure of a low-visibility landing. With past data indicating that the success of 1,200-foot RVR landings is about 50%, rather than an acceptable 95% to 98%, much testing and data collection leading to full understanding of this complex environment is warranted. Many possible solutions have been proposed, such as new displays, fully automatic landing, new guidance, etc., but no means exist for determining whether such solutions are suited to the real problem.

By testing with cameras in the aircraft and on the ground in a scientifically organized manner, the most precise data can be collected relative to many other parameters, such as RVR, ILS, wind shear, SVR—all critical landing regularity and safety parameters. Wheel heights at threshold can be determined to 6 inches and centerline offsets to a foot or less. Velocity data can be derived using precision timing references in the photo system. Typically three or more synchronized cameras are located in the approach, flare, and touchdown region of the runway. Similarly, two or three cameras aboard the aircraft are used to record path, actual cockpit (to ground references) visibility, and the absolute height of the aircraft relative to the exact touchdown elevation.

Standard cameras using moving film require a great deal of processing, but it is possible to use television type video recordings that can be used with automatic image analysis equipment to greatly automate the data processing. Obviously, an engineering study of this recording technique is required, but if used in visibilities of at least 1,000 feet with properly spaced, multiple cameras, full optical tracking of a landing below 200 feet is feasible. Radio or radar tracking simply is not adequate, and much FAA experience in this area has shown optics and film superior to electronics. Even so, many problems of film recording remain.

However, this is not to prejudice the method of data collection, but to indicate that a means of great accuracy is required and must be useful in low visibility. Effectively, the multiple cameras can acquire detailed optical records of the landing path which, after subsequent computer analysis in the laboratory, give the exact information on flight trajectories (Table III). The pilot is expected to conceive these operational conditions in the real-time environment of a few seconds and very limited visibility.

Thus, the combination of modern optical tracking concepts with jet aircraft operating at an airport where fog conditions can nearly be guaranteed allows a scientific means for analyzing the low-visibility landing operations before actual public exposure occurs. Airline pilots have stated consistently in several air safety forums that they have serious doubts concerning the present VHF/ILS authorization. A large statistical base must be developed for CAT II and III since the commitment to an actual landing is often effectively made at or prior to visual contact in such conditions. The go-no-go decision often cannot be altered by the pilot because of limitations in flight dynamics and his legal (visual-radio) information inputs.

In fact, there is reason to believe that some fatal illusions exist in the low-visibility landing conditions, creating visual pitch and height input cues to the human pilot that are so erroneous as to lead to a crash. Although this has not been scientifically documented, since many of the pilots involved in these suspected conditions have perished, the pilots that have survived indicate such illusions may be very significant.

TABLE III

TYPICAL DATA DERIVED FROM PHOTO THEODOLITE LANDING TRAJECTORY ANALYSIS USING PORTABLE EQUIPMENT AT A MAJOR JETPORT

Aircraft Type	Landing No.
Runway Heading	Ceiling
Wind Velocity	Wind Direction
Altimeter	Ht of Wind Data

1. Average approach angle (deg) =
2. Distance to threshold from a height of 50 feet (ft) =
3. Flare-point distance to threshold (ft) =
4. Flare-point height (ft) =
5. Threshold height (ft) =
6. Threshold ground speed (knots) = CCAS =
7. Main gear touchdown distance from threshold (ft) =
8. Touchdown ground speed (knots) = CCAS =
9. Speed bleed-off (knots) = CCAS =
10. Nose-wheel touchdown speed (knots) = CCAS =
11. Threshold flight path gradient (deg) =
12. Average gradient at 2 seconds prior to touchdown (deg) =
13. Displacement from centerline at threshold (ft) =
14. Displacement from centerline at main gear touchdown (ft) =
15. Displacement from centerline from a height of 50 feet (ft) =
16. Displacement from centerline from a height of 100 feet (ft) =
17. Displacement from centerline from a height of 150 feet (ft) =
18. Maximum gradient in approach (deg) =
19. (A) Nose-wheel touchdown time after main gear touchdown (sec) =
    (B) Distance from nose-wheel touchdown to main gear touchdown (ft) =
20. Sink rate at main gear touchdown (ft/sec) =
21. Ground speed at a height of 50 feet (knots) =
22. Body angle (deg)
    A. At threshold =
    B. At a height of 50 feet =
    C. At main gear touchdown =

With NASA's AMES Research Center located near Arcata, the basic aircraft crews and support could come from this location. Furthermore, close liaison would be maintained with the fog chamber and electronic simulation under way in nearby areas.

F. <u>GENERAL AVIATION TEST FACILITY</u>

A general aviation test facility might be located at one or more flight centers such as a university (Princeton and Ohio University are examples), and/or at a flight research center of NASA, such as Langley, Ames, or Edwards. The purpose of this facility would be to provide a national testing basis for general aviation aircraft and their ATC equipments. This can be illustrated with an example. Although much promise is offered by a VLF navigation system such as Omega for providing a simple, very-low-cost Area-Nav system for general aviation, a great deal of test work and analysis is needed before such a plan could be implemented. Most of this general aviation work is directed toward single-engined aircraft so that, for testing purposes, small airfields, small hangars, facilities, etc., are quite adequate.

A continued example is flight research of the coverage of VLF signals, effects of noise, pilot display of the oblique-parallel lines of position, and a possible means for a "roll-call" reporting of position to a centralized ATC system. Since the errors of these VLF or LF coordinates would be constant throughout the local coverage (rather than varying by as much as ten times along a track as in VORTAC), entirely new concepts for training student pilots to use such a simple system would be in order.

The simplicity of the signals, contiguous coverage at all altitudes, displays, and ATC application of oblique-parallel coordinates when combined would be much more suited to teaching student pilots the rudiments of instrument flight (than VOR-DME and Area-Nav--the VHF-UHF equivalency). Upon completing instruction, the newly licensed private pilot would have the minimum capability of locating himself in flight. Some low-cost simple means will also become essential in a short time for geographically avoiding certain airspace or to locate remote destinations. The ability of general aviation to legally and responsibly avoid certain controlled airspace assignments or to readily utilize other airspace provided for improved general aviation ATC services must become readily available in our national ATC plan. VORTAC Area-Nav systems costing from several thousand dollars to 20 or 30 thousand dollars will probably not suffice at the cost levels herein envisioned. Avoidance of other aircraft and airspace by visual means is becoming limited if not unrealistic in many parts of the country.

Testing of the general aviation aircraft with varying levels of ATC equipments on board, such as VOR, VLF-Nav, transponders, altitude reporting, communications, simple narrow-band data links, etc., would provide a source of knowledge relating to the ability to engineer facilities for these large numbers of aircraft and pilots. The goals of lowest-cost airborne units suited to pilots of minimum skills would be researched. Good system planning for ATC compliance would be sought by tests at these facilities. Simple proximity warning devices to provide alert or warning signals to other general aviation aircraft and perhaps more importantly to signal to airliners also need accelerated investigation.

While military aviation has several major centers for development of all its needs, such as Wright Field, and the airlines depend heavily on the large resources of their own engineering staffs and such companies as Lockheed, Boeing, and Douglas, the economics of general aviation usually allow little for equivalent development of its needs. The much lower cost of the general aviation aircraft (single-engine aircraft) and the dispersed market are factors not conducive to pooling any form of nationally supported resources for development.

Some may feel that any effort to pool resources for the improvement of general aviation is catering to a small minority. However, another view is that, by sheer numbers alone, general aviation is quite representative of the public. More important than these arguments are factual statistics showing that the safety record of general aviation is very poor.

The threat of general aviation aircraft colliding with airliners does place some burden on government agencies to provide a means, suited to the economic limits of general aviation, to reduce this threat without constraining general aviation. Similarly, the public is exposed to this type of aircraft operation when using air taxis and when flying for pleasure and business. Many important persons using such aircraft have died in recent years because of landing accidents, running into mountains, and by air-to-air collision with other aircraft.

It would seem well within the concepts of public value and safety to create two or three R & D centers for developing improved general aviation to the point where its safety record is greatly improved over what it is today. To simply regulate general aviation by reducing the airspace available, requiring more and more "airline" type avionics, and to increase user charges at airports that do have facilities is leading to confrontations with legal and safety overtones that can be better circumvented by a small investment in this type of general aviation test centers and/or facilities.

The dispersion of general aviation operations to the thousands of small airports (new and old) suited to their type of operation should be supported by ATC; furthermore, navigation facilities should reach these airports (VOR is often unavailable for letdown, or is too poor in accuracy), and some form of simplified control should be available at the busier general aviation airports. The potential of the two-dimensional LF or VLF systems to achieve this (since they have no "line-of-sight" limitations) is large and should be exploited. Perhaps, for a few thousand dollars, each small airport could have some minimal let-down, Area-Nav, and position reporting facilities suited to the speed, density, maneuverability, and flight altitudes of small general aviation aircraft.

G. VERTICAL SEPARATION TEST FACILITY

The most valuable dimension in ATC will remain the vertical dimension. With all the interest in better horizontal definition of airspace with "volumetric" landing systems (such as the SC-117 and Area-Nav using DME and VOR angle computations), it is often thought that the airspace will adequately be defined. However, in examining each of these concepts for improved horizontal use of airspace, one finds that full dependence on barometrically sensed altitude remains. Each aircraft uses its own measurement of pressure data to achieve vertical separation in ATC. The Area-Nav computers allow the combined use of VORTAC data and barometric data to compute vertical profiles, to provide vertical navigation on airways, and to provide descent paths toward a runway. Unpredicted errors in DME, VOR, or the barometric altimeter can be serious under such conditions of flying three-dimensional "slant" airways (see Figure 18).

The SSR ATC beacon system also depends on barometric pressure measurements. The aircraft replies (to a pulse interrogation) with a series of pulses (contained in a 20.3 μsec time period) that can be decoded to give both altitude and identity. The code structure is such that about 4,000 discrete codes are available for altitude reporting to ATC. Consequently, by pulse interrogation "interlacing," a ground rotating SSR beam solicits both altitude and identity during the short time it is passing and "dwells" on the aircraft. The barometric altimeter uses an (analog-to-digital) encoding disk which is varied by pressure; this effectively provides (via the transponder) the pressure data sensed within each aircraft.

This altitude data is quantized in 100-foot increments and is used in the semi-automated ground ATC computations for collision warning and conflict avoidance. The altitude data on each aircraft is also available to the air traffic controllers to assure that adequate vertical separation between multiple tracks exists. Much is made of this automatic altitude reporting system, and it is of great significance to our national ATC plans.

There are several barometric altimeter errors that have been defined by previous studies. Experts in the design of barometric altimeters continue to reduce errors by such means as servo-driven gears to reduce drag on the pressure capsules that make up the heart of a barometric instrument. However, this increases costs considerably beyond the means of general aviation. The object of the barometric capsules for providing the mechanical power to drive the indicating hands and the altitude encoding disks leads to errors in the system. The actual separation between two aircraft that are vertically separated by ATC implies that the tracks in their respective, assigned horizontal layer of airspace can cross over the tracks of other airspace layers. Unfortunately, this separation is the difference between two independent sensing units in two separate aircraft. It is often the small difference between two large, independently measured quantities--for example, an aircraft at an altitude of 11,000 feet and another aircraft at an altitude of 10,000 feet are represented by 11,000 minus 10,000, or 1,000 feet.

Friction, pilot setting errors, ground reading errors, rapidly changing frontal conditions, static line errors, hysteresis, etc., all can contribute in one way or another to afflict the ATC separation accuracies. There is at present no way for a pilot in flight to be aware of these errors, and he must fly with a high level of faith. The ATC system must also accent this high level of faith whether it is warranted or not. It does not matter if an airliner with a 30,000-dollar servo-driven, dual installation is within 200 feet of its correct altitude, if the vertically separated traffic consists of a general aviation aircraft with a low cost and possibly poorly calibrated altimeter.

From the pilot's and controller's viewpoint, an erroneous altitude reading is as convincing and believable as a correct altitude reading as no alternative exists but to accept at face value the displayed altitude or the transponder report of altitude to the ground ATC system. It is often the difference between two large readings in a ground ATC computer that creates the degree of vertical separation. A recent report by the FAA (Appendix C-6, DOT/ATCAC report) states that little quantified data on general aviation altimeters is available, but that the data that is available indicates that most errors are "within $\pm$600 feet with maximum deviations to 900 feet." This is quite unsettling to dense ATC concepts. Bench checking with good standards of only the instrument does not include the many other in-flight errors that can jeopardize vertically separated traffic.

With the expansion of barometric encoded instruments to general aviation aircraft (about a 500-dollar addition to a 1,000-dollar ATC transponder), it will soon be possible for ATC to automatically determine what each aircraft is reporting in the way of height information. A vertical ground-based radar can measure the aircraft's height to 10 feet or so relative to the elevation datum of the radar. This ground altitude data is used to check the barometric air data. The facility that would be developed here would be an electronic means of establishing independently the true height of the aircraft and comparing this with his reported barometric height. This facility would be effectively a "quality control" measurement making "spot-checks" on the most critical and precise measurement utilized in ATC. Obviously, if the possibility of a 600 to 900-foot error is prevalent, one cannot continue to assume safe handling of air traffic in 1,000-foot layers that assume $\pm$500 foot separations for about 6 sigma exponential values.

Good engineering practice would suggest that the error of the barometrically sensed altitude information be such that with all errors combined on a 3 sigma basis, the total error be less than 250 feet. This would mean that two vertically separated aircraft each in error by 250 feet would still be separated by 500 feet. The 500 feet would allow for the values in excess of 3 sigma which, though small, are of real significance when one considers the millions of operations involving the proximity of two aircraft that depend fully on vertical separation. The tens of millions of operations that use the altimeter data to clear physical obstructions (mountains, landing approaches, etc.) is also of great concern, since far more fatalities occur in this category than in mid-air collisions of two aircraft.

H. VERTICAL DATA COLLECTION FACILITY

The vertical data collection facility would be mobile in nature with the ability to interrogate the aircraft SSR transponder (on 1030 MHz) when it is overhead to obtain its reported (via transponder) altitude for comparison with the independently measured altitude. The test facility would then determine (1) the instrumental error (difference between the independent, radar-type, measurement and the SSR coded reply), and (2) the flight error (the difference between the ATC assigned altitude and the actual instantaneous altitude). The latter is obtained by monitoring ATC instructions to the aircraft flying overhead of the test unit. To assure that the aircraft flies directly overhead (or nearly so), the test unit is located along an airway or an ILS approach path to a runway. By means of slant range corrections, the independently measured radar height does not include errors due to the aircraft not being directly overhead. Various simple means exist for making this correction in the measurement so that aircraft need to pass over only approximately in the vicinity of the measuring units (not necessarily through the zenith angle above the facility).

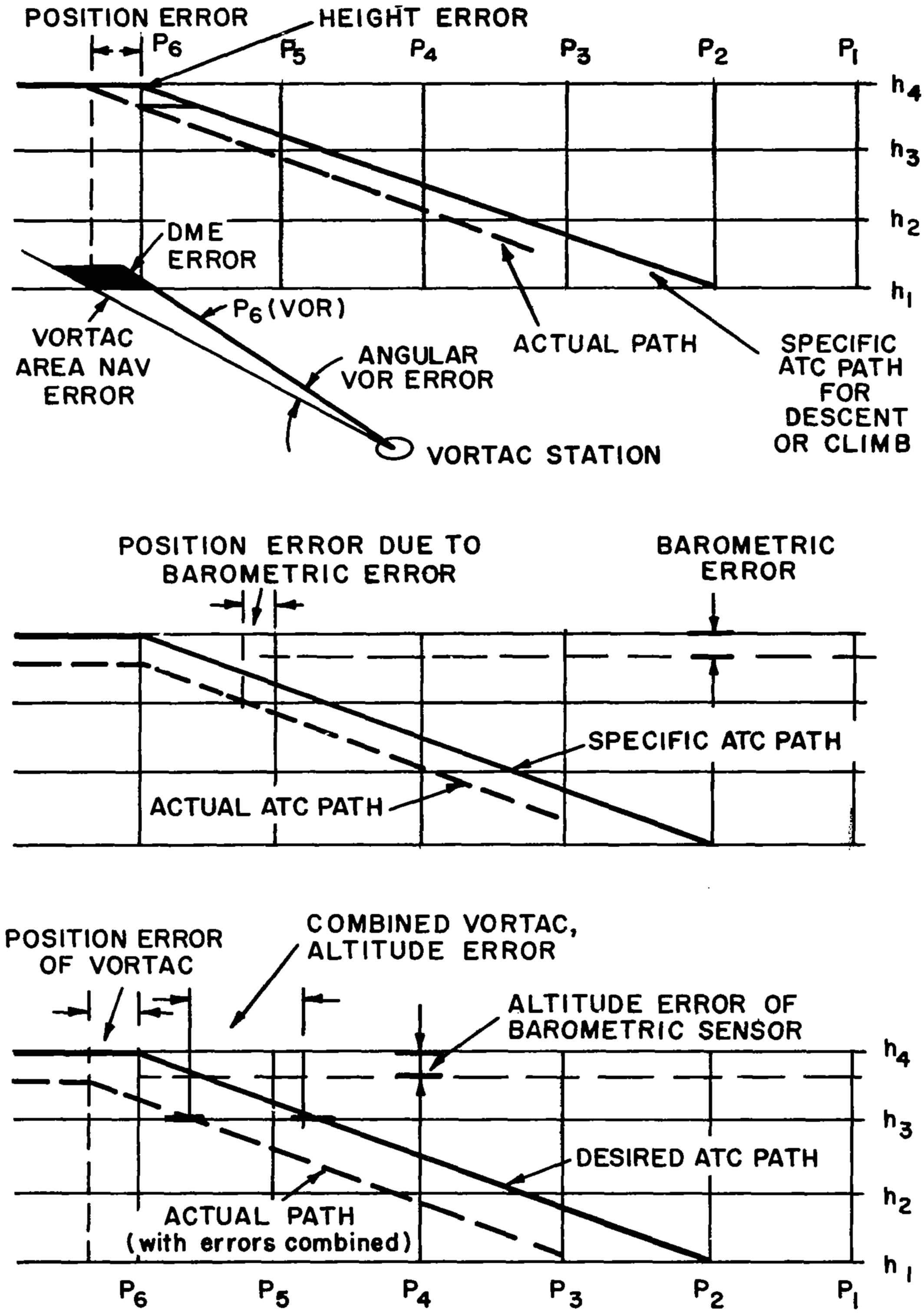
The data output of the SSR and radar height measurement would be automatically recorded in digital form--the original SSR altitude data being already in this form. By establishing a national program--with some dozens of low-cost data collection units located throughout the country--statistically acceptable information about this critical ATC input can be collected for the first time in the history of ATC. Independent of pilots, operators, or agencies, a realistic appraisal can be made of how high the risk is with vertically separated air traffic.

Although no regulatory action is intended or should be allowed during the data collection phases, it will be obvious who the offenders are. They will have no knowledge of the test or extent of height errors, but they can be quickly notified to correct their instrumentation and avoid any future situations of hazardous vertical separation. Unless some national measurement effort is made, and a continuous feedback to the aircraft, pilots, and the instrument makers established, we may simply jeopardize, unwittingly, the safety of the national ATC system.

We must have quantified, statistically valid information relating to these altitude error values in ATC and either control and monitor them to within acceptable limits, or increase the amount of vertical separation in ATC. It is unwise to proceed without this knowledge into an automated ATC (ground processing) system whose computers employ 100-foot reporting accuracies for vertical separation and specific sloping airway computations (using only VORTAC) of many forms when we suspect errors up to 900 feet. Some scientific data must be available concerning the statistical nature of actual in-flight measurements of altitude errors. It is the in-flight functioning or ATC-pilot use of the altimeter that can be fatal, not how well it performs on a bench in the hangar.

Once this data source is statistically sound, based on, say, 2 years of data collection throughout the airway system using 30 or so collection vans, the automated national ATC system can then be "programmed" with confidence. To assume this knowledge on vertical ATC errors exists today is to assume that someone has really measured statistically valid quantities. Surprising as it may be, this is not so (as confirmed by the FAA), even though altimeters have been used since before the early flights by the Wright Brothers. No "in-flight" measurements exist for all types of aircraft flying at the various speeds and flight configurations used in ATC. Only in rare cases is this data available.

The collected data base would first be used for a national assessment of the safety of the "tight," vertically separated airspace concepts now being formulated for Area-Nav, sloping airways, and terminal area controlled airspace (see Figure 18). Once this data base is adequate, then the system would remain as a national calibrating-quality-control facility along selected airways for pilots to obtain data on their altimeter errors while in flight. Several means exist (including a voice automated tape from the ground) for informing the pilot or an aircraft overhead (the facility) of his independently measured



VORTAC AND BAROMETRIC ALTITUDE ERRORS IN AREA-NAVIGATION ATC CONCEPTS

FIGURE 18

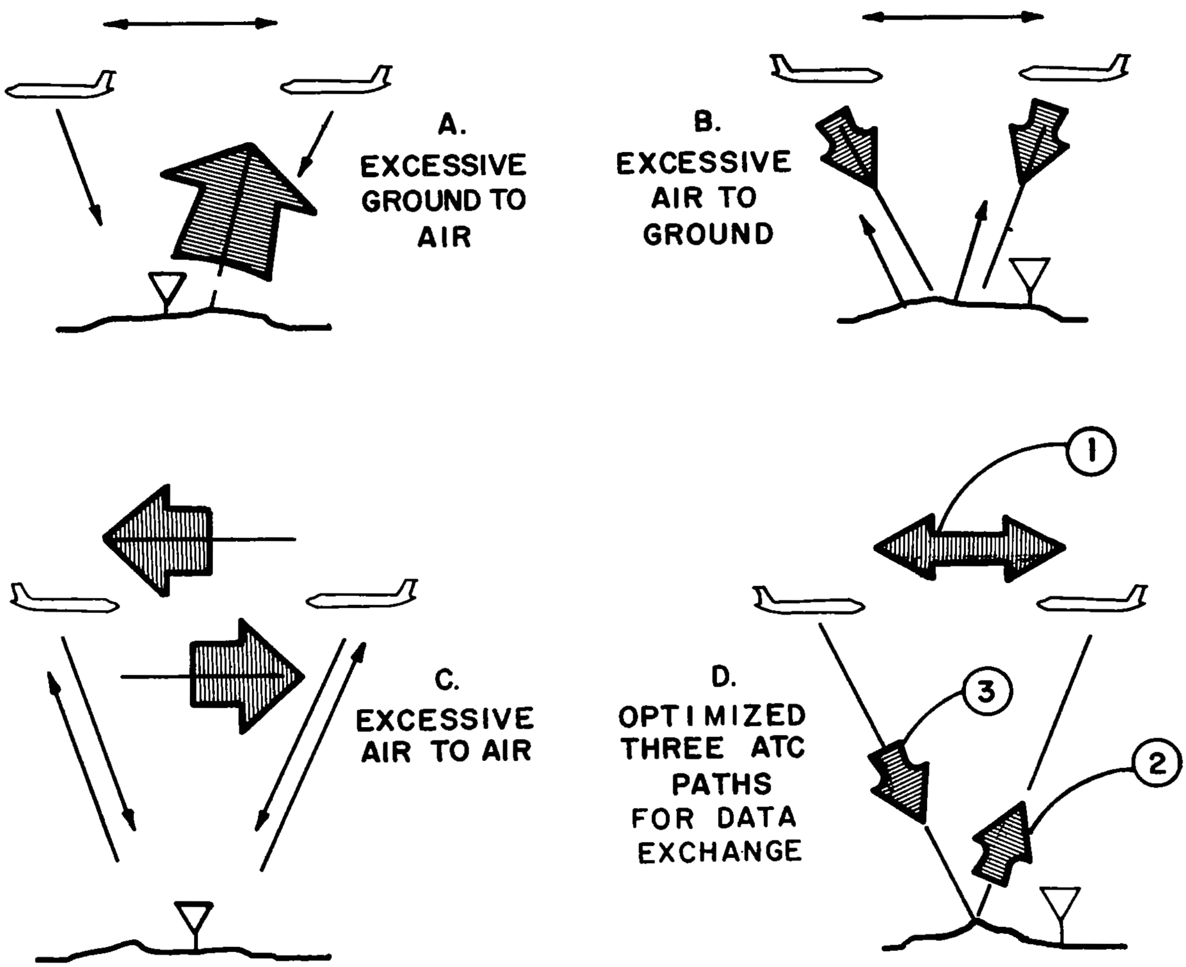
height and possibly even the error and polarity of his altitude reporting using ATC transponder codes. Again, since tens of thousands of aircraft will be using these transponder altitude reporting means shortly, such a test facility should be quickly developed and deployed. A basic R & D tool for the designer of ATC systems will then be available, making an acceptable science of utilizing the most critical dimension of ATC technology.

V. ATC INFORMATION EXCHANGE BETWEEN PILOTS AND CONTROLLERS

A. AIR-TO-AIR, AIR-TO-GROUND, AND GROUND-TO-AIR SIGNALLING

In the total exchange of data for navigation, air traffic control, and landing guidance, considerable information must be passed between pilots and the ground controllers concerning the flight of the aircraft. Currently, much more data must be passed from the ground to the aircraft than from the aircraft to the ground. It is also not a moot question as to whether there should be air-to-air exchange of data and, if so, for what purpose and in what form. To answer the last question, it may be necessary to first establish what data is exchanged between air and ground before examining the needs and interfaces of an air-to-air signalling system for exchange of data directly between aircraft. An optimized flow of information along three critical ATC paths is essential to maximizing system capacity and lowering total national costs. An ATC system with an imbalance, such as excessive ground-to-air data exchange and lower capacity, increases costs and raises questions of safety, training, and added burdens on ground controllers. The current ATC system is probably suffering from this imbalance as noted in Figure 19.

The ground-to-air data exchange is in the form of aircraft reception of ground-originated signals of navigational data such as VOR, DME, TACAN, ILS localizer, ILS glide path, Marker Beacons, voice communications, SSR interrogations of identity (1030-MHz path), SSR interrogations of altitude, and similar data. The air-to-ground data (that is, data originating in the aircraft and transmitted to the ground) is in the form of SSR replies (on the 1090-MHz path) of aircraft identity (one of 4,000 codes), altitude in coded form, and position (range-angle) such as used in a surveillance radar. Also the pilot's voice communications reports are an important part of the air-to-ground flow of ATC information as is the air origin of the DME signals. Auxiliary ATC data originating from weather radars,



VARIATIONS IN THE THREE PATHS OF INFORMATION TRANSMISSION IN ATC

FIGURE 19

radio altimeters, Doppler navigation systems, and proposed proximity or collision detection systems also are air-originated signals but with only airborne use of the data, the ground deriving no gains.

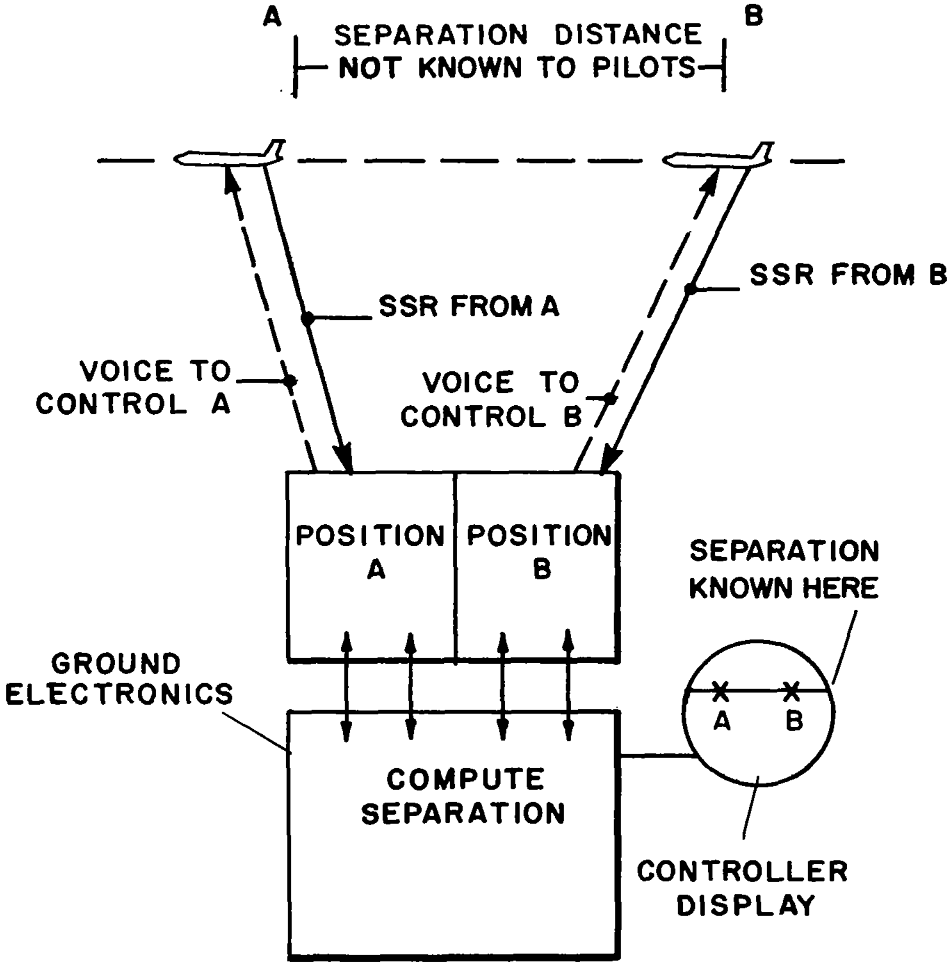
As seen in this brief survey of the exchange of signals, several systems are engineered to create this balance of ATC signal transmission paths, so that the ground controllers are as well informed as the individual pilots concerning the aircraft's current and future flight path. Since ground signals, such as SSR, have the advantage of fixed references, efforts must be sustained to inform the pilot of information pertinent to him, such as his own track and schedule and the radio guidance and ATC data inputs. The amount of information available to the pilot relating to other aircraft in the area is usually limited to proximity cases such as ground-originated voice data reporting the proximity of aircraft flying in a certain direction and at certain different altitudes with respect to the subject aircraft. The desire to provide a full ATC display of all aircraft as the ground controller uses is a natural one, but would confuse the pilots and essentially make controllers out of each pilot, so that the centralized management and decision process--essential to safe ATC--can be negated. Thus, too much as well as too little information for the pilots is undesirable. Probably the main difference in applying a "picture" of air traffic is that the ground controller always uses fixed reference coordinates for determining the relative position of two aircraft, while the pilot, being in an aircraft with moving and continuously changing coordinate information, is dealing with a "floating" coordinate system varying in three displacement values and three angular values.

Some planners think that more air-to-air data exchange should take place for various reasons, the most important being collision avoidance and warning of proximity of other aircraft. Of course, air-to-air voice contact can take place today since nearly all ATC functions involving voice are on common (simplex) radio channels so that without switching a pilot can hear instructions to other pilots in his vicinity and benefit from this. He can, if the occasion arises, talk directly to another pilot since with simplex both transmitting and receiving frequencies are common and messages are time-shared. However, usually the ground instigates nearly all voice data transmissions (as noted in Figure 20) with but few transmissions between pilots only.

Thus, we should investigate the value and extent of air-to-air signalling and how it coordinates with the ground-to-air and air-to-ground exchange of ATC related data. This third (air-to-air) path of data exchange, if overdone, can be confusing to the pilot, since only the ground central ATC system elements are capable of assessing the multiple flight paths, flight plans, track velocities, airport loading, altitude separation, etc., so essential to high-density operations involving thousands of potential interactions between hundreds of aircraft daily in a given geographical region. Because the ground is technically more suited to many of these functions, it may be that ATC has gone too far in this direction, leaving the pilots somewhat "out of the act" and placing too much burden on ground controllers. This requires excessive numbers of controllers and excessive numbers of control sectors.

B. CONFLICT PREDICTION---COLLISION AVOIDANCE/PROXIMITY ALERTING

Conflict prediction is one of the basic functions of the centralized (ground oriented) ATC system, using the coded transmissions from aircraft and the computer processor equipments for predicting conflicts, and more importantly resolving them prior to any proximity case that is unplanned. "Collision Avoidance" is not usually part of the ATC language as conflict prediction and resolution effectively create tracks, schedules, and routings that do not create a common occupancy of the same airspace by two aircraft. "Collision Avoidance" is a poor choice of terminology as it infers a failure of the positive thinking and intent of air traffic control facilities.



CURRENT SYSTEM TENDS TOWARD CLOSE CONTROL WITH SEPARATION COMPUTED FOR CONTROLLER AND NO DIRECT INFORMATION FOR PILOTS

FIGURE 20

Furthermore, when the ground detects a potential conflict, the solution (to avoid subsequent conditions of "proximity" or "collision") is usually a change in heading, change in track speed, or perhaps a change in altitude. The significant point is that all maneuvering options are open to the ground solution, since full data about track, heading, speed, and all other adjacent traffic is known. Collision Avoidance Systems (CAS) typically give but one limited option, that of changing altitude, and are not capable of using the other options of heading, track velocity, etc., open to the ground. Furthermore, CAS concepts only accommodate two aircraft and ignore the impact of the two aircraft solution on others. Limited climb or dive commands ignore any third aircraft, or for that matter other orderly aircraft following the ATC instructions which are optimized for all air traffic, not merely two aircraft.

This is again the result of CAS "floating" coordinates. Even a vertical change is the poorest and weakest of the avoidance options, since barometric data is notoriously weak. Another part of this report suggests means for minimizing excessive barometric errors.

Most CAS systems, being based on airborne coordinates between two aircraft, operate differently from ground systems [see survey in the Institute of Electronic and Electrical Engineers (IEEE) Transactions; AES-4, No. 2, March 1968, and in the IEEE "Spectrum" issue of August 1970]. Since the air-derived CAS data concerning another aircraft is primarily range information, this range data and its rate of change (range-rate) is a computation to evaluate whether a target is closing toward the subject aircraft. However, all aircraft must carry fully compatible, standardized and sometimes costly equipment to make the CAS system foolproof. Only aircraft that install new, fully compatible, fully spherical signal coverage, working in full concert, are protected. CAS does not use signals available from other sources in the air or from the ground. Some ATC experts think this "independence" a virtue; others think it a major fault as it duplicates and usurps ATC functions [including proximity warning indicators (PWI) and CAS] better solved by other means.

The FAA now requires that all aircraft operating in many of the high-density areas carry SSR-ATC transponders, and this requirement is likely to increase the total areas affected. Having done this, the ground automatic system can track all aircraft, since they reply to ATC with strong ground-to-air signals with position, identity, and altitude established early. Any potential conflicts are thus detected much better than is the case with CAS, and ATC control modifies and re-directs traffic in the one best manner, selectable from many options, that fulfills the exact need of the occasion. A slight heading or speed change modifies a potential conflict well before a "proximity" exists and does not create the undesirable emergency situations of CAS, and pilots do not receive false alarms. The CAS system is based on the aircraft climbing or descending if the exchange of altitude range and range-rate reports of the two cooperating aircraft indicates common position-altitude occupancy (within tolerance limits of their barometric sensing). As noted, from an ATC viewpoint, this is a very restricted solution, since often in ATC practice altitude layers are independently sensed and controlled, and the two aircraft would then possibly create a further series of ATC conflicts because the CAS maneuver is by its very nature totally unpredictable and unscheduled. CAS is an emergency and there are ways to engineer ATC concepts that do not depend on emergencies.

C. ALERT SIGNALS REPLACE CAS SIGNALS

The alerting function (alert only—no maneuver commands) may be more readily achieved by using some of the SSR transponder signals to alert (only) another aircraft in the vicinity of the "presence" of the proximity situation, and at the same time using the SSR codes to automatically signal this condition to the ground ATC computer displays, using the same SSR system signals, displays, etc., already committed nationally.

In this redundant, SSR-manner, if for some reason the computing, tracking, and display system of the centralized ground system is at fault, the air-to-air detection of the other aircraft's transponder signals would be used in the automatic alert to the authoritative ground system. These air-sensed proximity signals using available, special, assigned SSR codes would in turn by-pass all local computer programs, attracting the human controller immediately to take over. The proximity case is then resolved by the many maneuvers that can be selected from the ground using fixed coordinates. The controller can also determine the identity of each aircraft, and a solution is immediately known to all parties, and confusion as to which aircraft will make the evasive maneuver is avoided. The maneuver does not result in a chain reaction in dense traffic as is possible with CAS concepts.

The ground sensing of the air-to-air (SSR) signalling of the proximity case may be such that the alerted controller determines that all is safe and that the close passage of the two aircraft is perfectly safe and is in accord with the ATC plan and criteria. This concept avoids the "false alarm" deficiency of the "independent" CAS systems, yet adds redundancy and safety to ATC, catching blunders, controller oversights, and computer programming and processing errors.

Normally these SSR proximity signal cases are not false alarms to the pilot (calling for rapid climb or descent), but may be "alerts" to the pilots to check with ATC or to expect a less violent maneuver that is known to be optimized; when executed this maneuver will not trigger a second proximity case with a third aircraft because of the first maneuver. Often the SSR proximity alert would not involve a maneuver, while in the "independent CAS" case this cannot be assured. All CAS commands must be blindly followed by the pilot. The reason that "no maneuver" will often be the conclusion, even with an air-to-air sensed alert, is that to effect the positive control of dense air traffic, planned, close spacings will occur and are quite safe if the tracks and closing velocities are under centralized, common, ground control. With ATC, each flight in three dimensions and time is integrated with all other air traffic in the vicinity. This principle is the essence of the centralized SSR system, using continuous airborne pulse transmission of altitude, identity, range, and angle.

D. CONFLICT OF AUTHORITY IN ATC

Among other limitations, it is the inability of the independent CAS system to fully integrate into the major, national ATC program (based on SSR transponders) that creates what can be serious operational and safety conflicts, since effectively two authorities exist--one in the air and one on the ground. In the case of pilot-initiated maneuvers of climb or descent the air authority is basing decisions on limited data; the ground authority, however, can have much greater data with much greater assurance and accuracy, consequently, its decisions must predominate as they can affect many other aircraft than the two proximity aircraft.

Thus, any weaknesses of the automated ground system (justifying CAS)--programming errors, controller oversight, or equipment failure--can be overcome by a supplemental but fully compatible air-to-air signal using air-transmitted, sharp pulses of the SSR system. Since now some forty to 50 thousand aircraft transmit pulses in reply to all SSR ground stations (overlapped interrogate areas), there are many replies available from all nearby aircraft that can be synchronously examined in each aircraft for range (and possibly angle) to alert the subject aircraft if other aircraft are too close. Before a maneuver is executed in the SSR-proximity concept, the proximity signal is relayed to the ground, and the ground determines what is suitable. Confidence in equipment functioning is established because the transponder is known to be operating merely for the aircraft to be accepted into the SSR system. Consequently, fail-safe, and ground-air alerting functions are assured by SSR. A CAS equipment failure can go undetected by both air and ground.

It is possible for ATC to utilize various levels of the SSR air-to-air signalling where only simple warning signals can be given the general aviation pilot with a $300 unit. Or, the same SSR air-to-air signals can provide relative location (such as altitude, range, and angle of the proximity aircraft) using more sophisticated equipments in airline and military aircraft. Thus, if the ground ATC does request a rapid change in flight path, the pilot is expecting it, is aware of the reason, and can, in the case of sophisticated airborne units, actually monitor the results.

In this manner all parties are protected. Once the required transponders are in all aircraft planning to fly in selected areas, everyone is protected even if a PWI is not added to all transponders. Clear authority for ATC maneuvers is established. Furthermore, the central authority and safety of the ATC system is not challenged, and PWI (or CAS) becomes an integral part of the transponder and the ATC system's displays, computers, etc. It adds at little cost the important "proximity-alert" to a successful ATC system now being implemented.

To assume that the national effort of ATC will require a separate CAS system suggests various weaknesses, which if they exist must be corrected, since even the most ambitious CAS proponent does not suggest actual ATC can be derived from only the air-to-air signals. Fortunately, the same and possibly more benefits derived from an independent, costly CAS system should be obtainable from the already standardized transponder-ATC system, reducing costs and improving reliability and services.

E. AIR-TO-AIR EXCHANGE OF DATA IS PROBABLE

Thus, in summary, it can be said that limited air-to-air signalling may be accepted in due time in some form if it is an integral and common part of the current national surveillance system. It can act in concert with the central system as a check on possible errors. The conflict prediction capability existing in the full transponder-interrogator environment (with automatic track and conflict computation) will probably have such high integrity that this limited air-to-air signalling function will have more than adequate redundancy, thus avoiding a costly, complex, unwieldy imposition of another electronic system for only CAS. This is obviously an ATC area that at the present moment seems more serious than it will be in the future, since now tens of thousands of transponders are being added or are in use in general aviation aircraft in order to comply with ATC in general, and specifically to satisfy new regulatory procedures for entering dense traffic areas. Consequently, by force of history and success of SSR, essentially all aircraft will be transponder equipped that can be of concern in a dense traffic environment. Also, by 1974 nearly all critical ground areas will be under automatic surveillance by multiple, overlapping SSR interrogator signals using the coded altitude and identity messages. By then the full display and computer installations for both automatic and (ground) controller monitoring of any potential conflict will exist.

The current incomplete implementation of the SSR program admittedly leaves a few weaknesses for a short while. However, the need to go through such a major, costly, national program again for equipping what will be 100,000 aircraft with new CAS equipment for equal effectiveness will probably not be warranted. The very weakness the CAS is intended to overcome can shortly be overcome by the SSR system itself when fully implemented and with a slight modification for air-to-air synchronous sensing of pulses as an integral part added to existing data used in the air-to-ground signalling path.

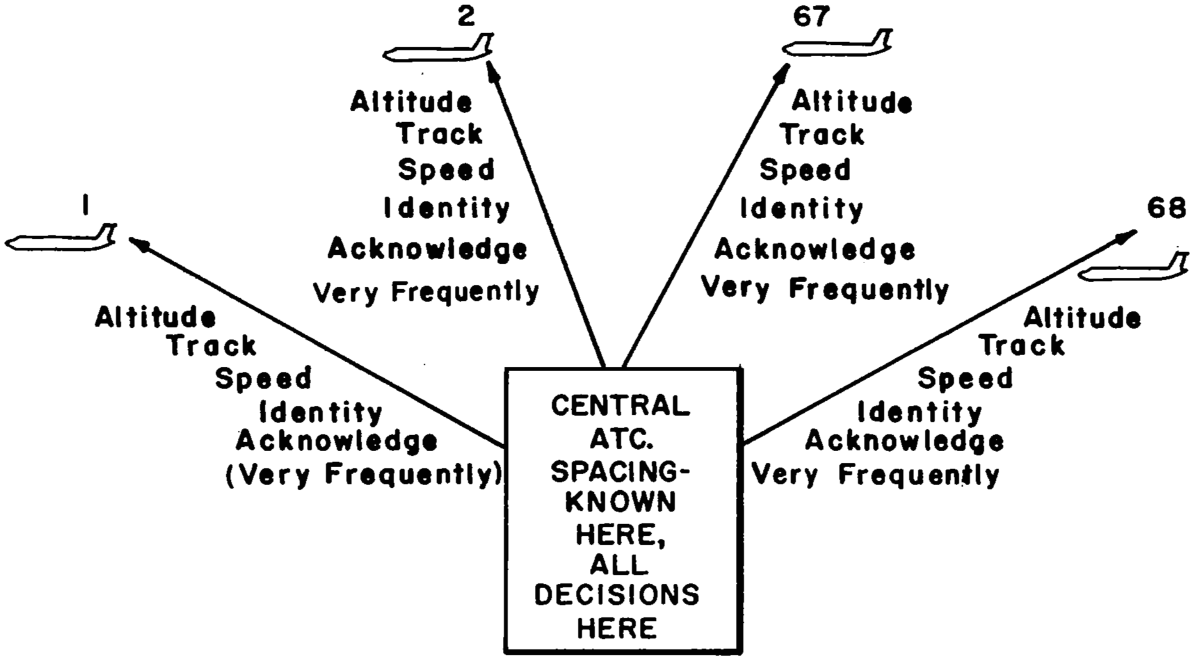
F. IMPLICATIONS OF AIR-TO-AIR DATA EXCHANGE AND ADVANCED PILOT DISPLAYS

We have covered some of the possible technology that can create a small change in the delicate balance of data exchange between the critical information paths used by ATC. The more conventional data transmissions of navigation and track information to the cockpit for use by the pilot to fly with respect to earth coordinates will need some further expansion to sustain the balance.

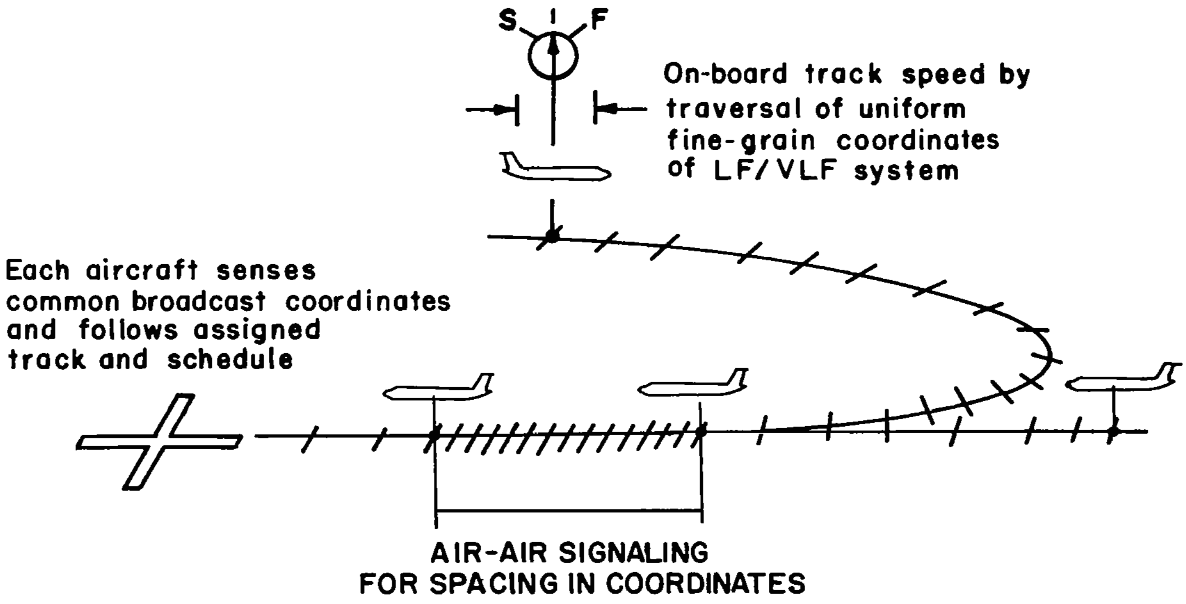
The air-to-ground transmission of data for use by the ground controllers is mostly based on the SSR interrogator-transponder system and voice communications. The many technical advantages of an earth-based interrogation and information collection system include high power, directive beams, multiple sites, permanent coordinates, large computer and processing capacities; when all combined, these advantages tend to emphasize the benefits of this (ground oriented) method of control. In the military case of controlling a fighter to a specific target, the ground controller "vectors" the pilot, instant by instant, by voice instructions to his target. Each aircraft under control must receive specific instructions relating only to his special circumstances. This concept of air traffic control is known as "close" or "tactical" control. Each individual pilot effectively changes heading, speed, altitude and executes other maneuvers only by the direct instant-by-instant instructions to only his aircraft from the ground control. Voice is used in most cases; however, automatic data links with visual commands displayed to the pilot have also been used in the military tactical control concepts. Often in "close" control the pilot is unaware of his exact location and depends on the ground for guidance as well as control, dispensing with normal forms of navigation.

An alternative air traffic control process which also has been tested in military applications is to use "broadcast" control in which the positional coordinates of the target are made available to the pilot but he navigates and solves his own intercept problem. The pilot uses the navigation system coordinates related to the target and his own coordinate location to follow the navigation system to intercept his target. Three geometric dimensions, time, and velocities are all involved. Both "close" and "broadcast" control concepts have been used in military tactical situations, and strong advocates of each concept can be found. Figure 21 illustrates these concepts.

If but a single or only a few aircraft are involved, "close" control has certain advantages. If large numbers of aircraft are involved either as interceptors and/or targets,



CLOSE CONTROL CONCEPTS



BROADCAST CONTROL CONCEPTS

BASIC CONCEPTS OF CLOSE AND BROADCAST CONTROL

FIGURE 21

"broadcast" control has advantages mostly relating to control of multiple aircraft. The major differences seem to lie in the problems of transferring information between air and ground in each of the concepts. Close control obviously requires more and more ground controller and ground-to-air transmissions as the need to control the aircraft increases with traffic volume. Increased density of traffic causes increased loading on this ground-to-air link in "close" control concepts.

In the interceptor case, the acquisition of the target with the airborne radar requires the "broadcast" control to merely place the aircraft near enough to the target to use the air-to-air data of the target's relative position for achieving the proximity situation desired by the interceptor pilot. Thus, when the air-to-air data is available to the pilot, it can be used by him, reducing ground instructions.

The tightness of the "close" control loop that continuously and precisely provides ground-to-air information to the pilot by steering and velocity commands is avoided in broadcast control. Although the tactical example does not apply directly to ATC, many similarities do exist. In other words, as the ATC controller controls more and more aircraft with more and more possibilities of conflicts (usually going up as the square of the number of aircraft airborne in a given area), then the instructions from the ground must go up geometrically. Since the pilot in ATC is unable to assess his progress relative to other nearby traffic, he must be continuously reassured when more closely spaced tracks or traffic is essential to give flow capacity to the system as typified by terminal areas. This means that the computer and the ground controllers then must continuously examine in real-time all the potential conflicts. The workload of ground ATC using "close" control concepts increases at nearly the same geometric rates.

In truly dense traffic cases, this "close" control method becomes a defeating concept of traffic control, since the human that must monitor the computer (and his portion of his control sector) can only issue so many instructions and examine so many conflicts. Furthermore, the pilot is increasingly concerned as he cannot determine whether all is well in his vicinity. This is why the FAA plans (based mostly on "close" control concepts) call for increasing the number of sectors. By nearly doubling them, and thus reducing each sector's area of coverage, the controller theoretically has the same number of aircraft to control but in less area. Once this increased sectorization occurs, the number of controllers must be increased by at least the same ratio so as to maintain some well substantiated ratios of "controllers per sector," "aircraft per controller," etc. One potential breakdown appears as the number of sectors is increased because the sector-to-sector transfer of information, known as "hand-overs," goes up again as the square of the sectors, or doubling the sectors will probably increase the sector-to-sector data transfer by about four times. Any fault in the transfer of the control of a flight (codes, identity, position, altitude, etc.) from one sector to another can be most serious. Consequently, the integrity of the ATC system is liable to be reduced with increased sectorization, assuming other matters remain constant.

G. MERITS OF "BROADCAST" CONTROL

It is imperative at this time in the history of ATC and at this critical phase of expanding close-control concepts to examine the merits of other basic concepts of the theory of air traffic control, such as the wider use of "broadcast" control methods. In this case the pilot is told to fly a given track with a given track speed and to meet certain checkpoints at specified times on the track. These can be mostly standardized conditions using codified tracks and schedules. The pilot's ability to fly suitable tracks for ATC improvements has been greatly constrained with the limited radial-only type of VOR tracks. VORTAC with computers (three-dimensional ones with inserted altitude and coordinates of all VORTACs) will at least initially aid, but as stressed herein it should in due time be supplemented or reduced by a navigation system that is truly suited (geometrically and in coverage) to this type of ATC track control.

It is accepted that the mechanization of Area-Nav at first will be with VORTAC, but VORTAC's many limitations can defeat the real gains of "broadcast" control that need superior wide-area coordinates. Such concepts as "broadcast" control requiring 5 or so years to develop, now need accelerated R & D emphasis. Furthermore, the close control concepts are already overloaded at times and have little remaining growth capacity. VORTAC Area-Nav is quite complicated since VORTAC is a complicated multi-point, multi-coordinate, and otherwise quite limited system for true Area-Nav.

ATC broadcast control concepts to be optimized must employ an excellent, very "wide," Area-Nav system.

H. RECTILINEAR VLF-LF COORDINATES FOR BROADCAST CONTROL

Elsewhere in this report it is urged that LF and VLF coordinate (and navigation) systems already in existence be thoroughly examined and possibly a new hybrid VLF or LF system be introduced that overcomes any of the transmission difficulties that have previously caused many to avoid their use. The techniques and engineering of a navigation system will not be discussed here other than to say that with modern knowledge of these low frequency signals and with the application of modern circuitry, all of the limitations of the past that restrain LF/VLF use can be removed. Validation and research is needed, but the rewards are so enormous in ATC alone that it is urgent we start some focused R & D in this direction. To avoid a technical engineering discussion of an LF/VLF system (that will divert us from an emphasis on ATC concepts), we will only consider the impact on the transfer of ATC information based on a wide Area-Nav system and typically assume that such a system is one containing the best features of both Omega and Loran-C.

We will examine the impact of such coordinates on ATC, personnel, control concepts, and other matters that will be greatly influenced by this change to a superior coordinate system. Basically, the coordinates can be visualized as one set of equally spaced parallel lines of position crossed by another set of similar parallel lines of position with the "angle of cut" (crossing angles) being between 60 and 90 degrees. The simplest case to visualize, and one often available to ATC (using these long baseline systems that are possible at LF and VLF), is a rectilinear system, just as if a rectangular graph paper represented the ATC and navigational coordinates. A single LF-VLF receiver obtains on board the aircraft both (LOP's) lines of position. Often more LOP's than two are available (usually three or four), and the user optimizes his position determination by utilizing only the best.

This coordinate selection means many things to ATC concepts of broadcast control:

1. Nearly constant granularity of track information (displayed to the pilot) is provided rather than the 10 to 1 variation typical of VOR data.
2. The average accuracy of the positional data is about constant throughout, typically ½ x ½ mile at the worst, or ¼ square mile vs VORTAC that varies from a fraction of a square mile to as much as 4 square miles or more. Often poor geographic control of accuracy prevails with VORTAC, where high accuracy is needed (see FAA AC 90-45 for example).
3. Nearly constant (and high) sensitivity can be applied in the pilot displays or autopilots for track-following on straight or curved tracks based on LF-VLF. Much lower sensitivity is required to accommodate VORTAC's (a) propagation bends, (b) angular dilution, (c) limited accuracy of VOR, and (d) station to station misalignment.
4. Enormous geographical areas employ a common LF-VLF grid so that all traffic can be compared in the same set of contiguous coordinates. For example, an area 1,000 miles by 1,000 miles can use common, contiguous VLF or LF coordinates while VORTAC would have several hundred separate, randomly spaced and uncoordinated sources of polar coordinates, each requiring examination and channelization by ATC and the pilot before usage.

5. The rectilinear-type*, constant-granularity coordinates at all altitudes allow uniform traffic control to all of the nation's 10,000 or so strips or small airports (remote from jetports) to be as good as that at jetports. This major advantage of ATC facilities for remote locations, in mountains, etc., allows dispersion of air traffic and lower average densities. VORTAC "draws" traffic into little "pools" to obtain better accuracy, while the long baseline LF/VLF systems avoid this and on the average are much more dispersive and precise, keeping localized traffic densities down.

There are many more comparisons between VORTAC and VLF-LF rectilinear type systems that can be made, but in order to emphasize the theme of some forms of cockpit control aiding in the total ATC system, we will now examine the possibility of having additional pilot functions, which is not possible with VORTAC. First, the pilot will note that the low altitude coverage of LF/VLF is of great value since the signals are retained throughout the flight (including approach and on the ground) so that his confidence and utilization of the signals is improved. If, for example, a given track is selected, defined by the crossing LOP's, he can maintain this track more accurately and constantly; since no switching occurs and no variation in coordinate accuracy is evident, convergence is avoided. The overall "control-loop" gain of pilot-track does not vary and can be optimized at higher gain levels than with VORTAC. He will thus fly specified tracks more precisely, and the sensitivity of his display can be improved to achieve this. Furthermore, it will be achieved with lower pilot workload.

I. 10:1 DISCREPANCY BETWEEN PILOT AND CONTROLLER ATC INFORMATION

The SSR system has often been used to check the VORTAC system accuracy simply because it is so much better (see FAA

* This phrase infers crossing angles of 90°-60° when used herein.

report NA 70-3, "Evaluation of Area-Navigation in the Northeast Corridor," Jan. 1970). This is not to quarrel with the scientific aspects of using one system that is about 10 times better than another for measuring performance of the poorer system as this is an accepted practice. It is, however, intended to point out that VORTAC data are that much worse than (SSR) surveillance data that such measurements are valid. If the VORTAC were accurate to about ⅓° rather than 3°, this SSR data collection of VORTAC Area-Nav tracks would not be possible.

This clearly focuses on one of the great weaknesses in today's ATC systems, namely, that the controller's data is about ten times better than the pilot's data, and the pilot is aware of this. In spite of pilots' desire for more participation in ATC, the emphasis goes to ground control since the controller has by far the superior information. This is merely the results of VORTAC equipment deficiencies and conceptual deficiencies of ATC based on VORTAC. Both deficiencies can be remedied. If the wide-area systems realized with VLF or LF can operationally realize ¼ to ½ square mile positional accuracies of LOP's, it seems quite possible (with the great amount of data now collected over twenty years time on Omega, Loran-C, Radux, etc.) that the actual cockpit information will be as precise as the ground controller's information.

The 10:1 discrepancy between surveillance and navigation will thus be eliminated with a new LF-VLF system of rectilinear type coordinates. Equally accurate systems for pilots as well as controllers will bring into being a vastly improved relationship between pilots and controllers. Such steps can optimize the ATC system by allowing improved ATC concepts such as broadcast control functions to be under the pilot's control. Effectively, we must now cater more to the pilot during the '70's to develop for him means that will allow his rightful and useful place in the ATC system. This is not to favor pilots but to achieve greater ATC capacity. Without at least the "basics" of precise coordinates in the cockpit equal to or better than surveillance accuracies, there is no hope for re-establishing the best balance between the pilot and controller for solving dense ATC problems.

Thus, we have developed the concept that both pilot and controller now have equally good information on the position of the aircraft that are active in an ATC environment. It also means that the coordinates of the ATC surveillance, computers, displays, etc., can now be "locked" more precisely to the "broadcast" control coordinates that the pilot will use for track following, for track velocity control, and for checking spacing with "fore and aft" aircraft on a common track. These advantages of improved track and spacing control using pilot's data need emphasis, since today the VORTAC coordinates are randomly located and poorly integrated in pairs and in fact change with the altitude of the using aircraft because of slant range DME errors. In effect, with SSR and VORTAC we have two polar systems; one for navigation using many randomly spaced and oriented VOR stations with relatively poor accuracy, and the second with many rotating, narrow beams, also generating polar coordinate data but randomly spaced and oriented.

By at least removing one of the variable polar coordinate systems (the VORTAC), we can now tolerate the latter. Also the latter (SSR) is preferred for retention as a polar ATC system for many operational reasons such as overlapped coverage for redundancy, etc. Now with but one randomly located multiple-polar coordinate system joined with a rectilinear type system, the two coordinates can be pulled together since the average granularity in each is about the same—about ½ to ¼ square mile. The overall ATC system can then be operated so that surveillance and navigation have equivalent resolution, accuracy, flexibility, and thus a harmonious relationship since each can be made to fully serve its user.

The pilot can now use cross-track velocity of the LF-VLF system for tighter control of the center of his ATC track and improve on the use of the airspace. FAA document AC 90-45 describes the application of VORTAC to computing of tracks (other than radials to the VOR), and it clearly shows the enormous amount of airspace that will still be unusable, even with Area-Nav, because of the VORTAC system errors. For a few short years of increased ATC loads this may not be of great significance, but it will in time accelerate in seriousness. With good, linear cross-track rate information it is possible for the pilot to program and follow a curved path and sustain the accuracy of the desired curved path. Climbing, noise abatement departures with turns away from communities is an important example of this use. When this is done with poor accuracy, large "buffers" of airspace must surround the track, denying that airspace to others and consequently reducing ATC system capacity.

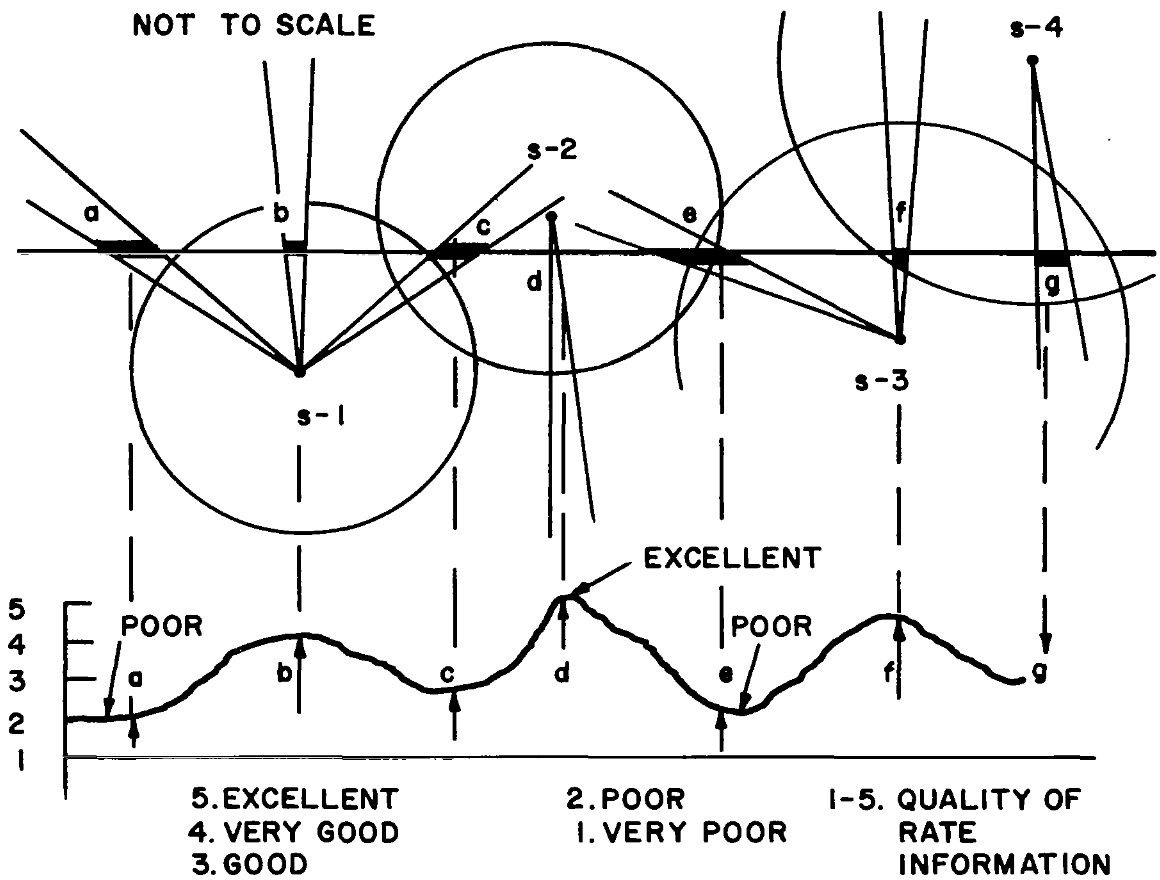
J. LONGITUDINAL TRACK SPEED

Another significant measurement to the future of ATC expansion is longitudinal track velocity. This airborne measurement is in many respects equivalent to ground speed but should be visualized as track speed relative to center of track, be it straight or curved for ATC purposes. If the granularity of positional information is high and uniform, then the track velocity can be measured anywhere on the track. Constant, known accuracies familiar to both pilots and controllers with minimum smoothing track time can provide good speed data. If, for example, 3% track speed is wanted, then a track about 30 times the dimension of track error (along its axis) will suffice.

For example, this 3% differential measurement with an RMS of 1,000 feet requires a track length of 30,000 feet. If an RMS differential error is 200 feet the track length is 6,000 feet, or a mile. In other words, track speed can be estimated by traversing the resolution elements of the coordinate system upon which the track is based. In the case of speed, it is the differential (that is, the change in the number of elements) and not the absolute accuracy that is of consequence. For example, the absolute positioning error may be 1,000 feet, but the change of position (positional differences from one end of a 1-mile track to the other end of the track) is but, say, 200 feet. This is effectively taking the rate of change of position to accomplish this. Smoothing over various track lengths provides various accuracies. The longer the smoothing distance, the greater the average accuracy, but the more sluggish the rate signal appears. Thus, high differential accuracies that are uniform over very large geographical areas are of great benefit to ATC and pilots.

One feature of a long baseline system is that, though fixed absolute errors are of a given magnitude, they do not suffer with short path errors or localized errors, such as "scalloping," "beam bends," etc., typical of VHF/VORTAC that can add unpredictable differential errors to short tracks used for establishing rate information. Rate smoothing over long track lengths, say 10 miles, is of little value to the pilot or to ATC since it takes too long to "read" a new track speed. Probably 1 to 2 mile track lengths requiring about 45 seconds of smoothing will provide suitable data on track rate. Thus, the rate information of VLF-LF tracks of a given length should be superior to typical VORTAC tracks of the same length by at least 10 times--a most important matter to ATC.

Any past experience to use this important ATC tool of track rate based on VORTAC can be poor since the flight track may be measured longitudinally by the angular system (at tangent points, say $\pm 3°$ at 30 miles the uncertainty may be 3 miles) so that the worst of VORTAC errors and track rates is often presented to ATC and the pilot (see Figure 22). Wide geometrical variations of VOR rate can be high and unpredictable. Varying VOR error along the (computed-offset by 30 miles) track gives wide changes in apparent track velocity. The long baselines of LF and VLF hyperbolae on a sphere tend to have parallel straight LOP's for 100 to 200 miles. Differential errors in LOP's are small, even over 200 miles or so. They can be so great in VORTAC (over 200 miles) as to involve two separate VOR stations with misalignments of $+3°$ and $-3°$, both figures falling within VORTAC performance specifications (FAA report RD 65-98, "VOR System Accuracy").



(s-1 to s-4 VORTACS 1-4)

VARIATION IN TRACK RATE AND ALONG-TRACK POSITIONING
USING VORTAC AREA-NAV

FIGURE 22

K. PILOT USAGE OF TRACK-SPEED INFORMATION IN ATC

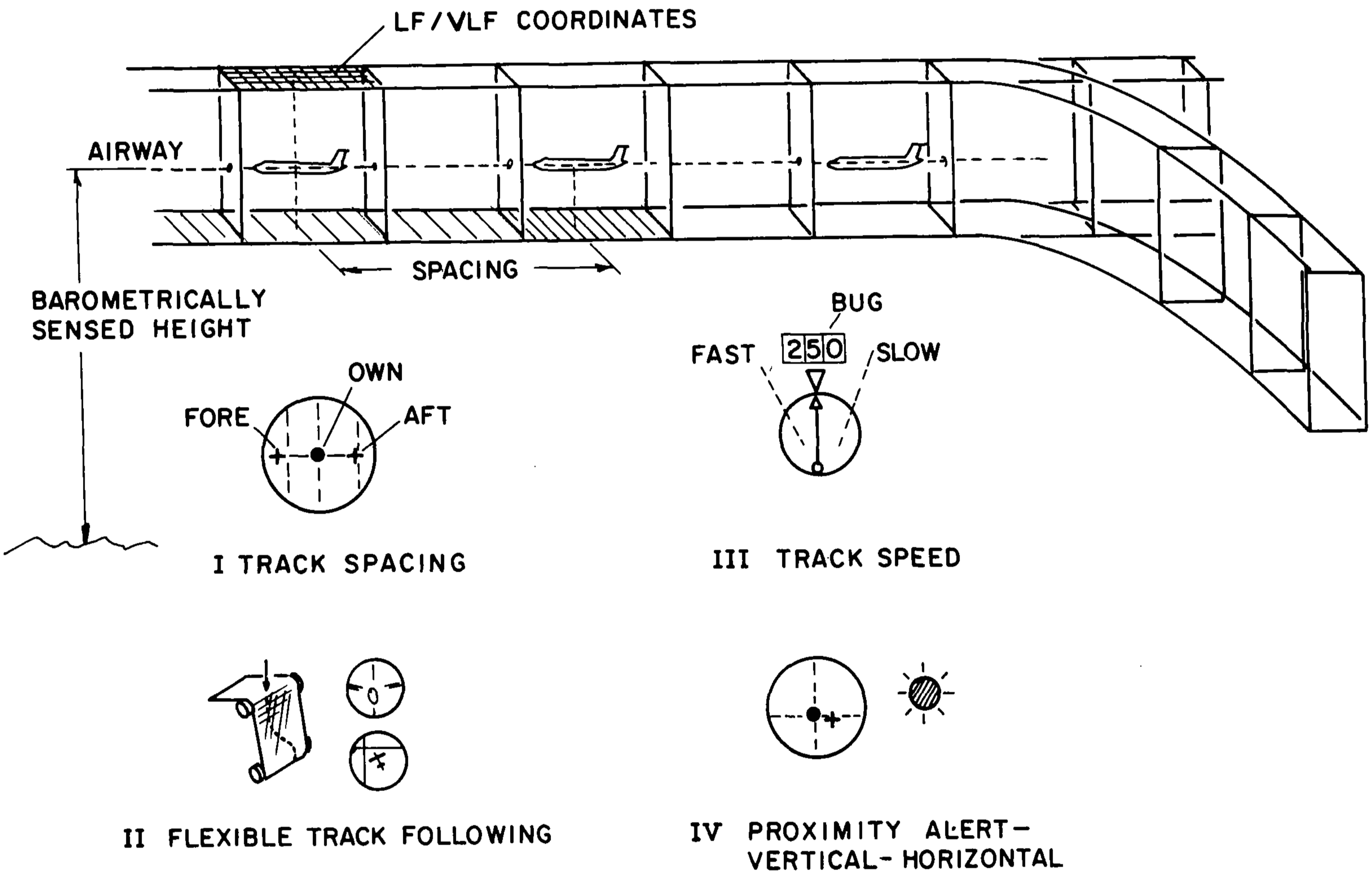
The pilot can now establish his (LF-VLF) track speed (velocity) using only on-board interpretation of rate of position change over a short track, and he can control his track rate closely so that if a nominal track speed is advised by ATC, all aircraft on the track effectively measure the track speed from the same source. This new tool for control in ATC differs from the pilot's use of airspeed, which is usually inadequate because of unknown winds, changes of heading, and different airspeed systems in different aircraft. Track rate using LF-VLF should also be superior to other velocity measurement means, such as Doppler-Navigation radars that suffer from high costs, independent measurements made over poor reflective surfaces that give varying radar returns, and varying track (ground speed) accuracies. The cost of measuring LF-VLF rate is low and the measurement is an integral part of the airborne receiver. In essence, all traffic and all pilots on a common track then measure track speed using the same common set of contiguous track signals. This feature alone will allow pilots to participate more fully in ATC and be more representative since they can see on a cockpit instrument how well they are maintaining the track velocity requested from ATC.

By some simple means of air-to-air data exchange (reception only) two pilots following the same track in LF-VLF (long baseline, rectilinear type coordinates) can station their relative positions (spacing) according to these signals. Since continuous switching between stations is avoided (as in VOR), long tracks and always the same basic coordinates are used in each aircraft. By using a simple roll-call of LOP positions along a track (airway), each aircraft receives the response of the other aircraft. Since the roll-call is based on time proportional to LOP, a continuous scan is provided. A roll-call period of only a few seconds will allow tone bursts of a few milliseconds to define a track, say, 100 miles long to a 0.1-mile accuracy. This is to say, a given aircraft pilot can establish the fact that another aircraft is ahead of him, on his track, spaced say 5 miles or 4.9 miles; and one behind him is spaced 4.7 or 4.8 miles. This roll-call coordinate reporting information using a VHF channel can then be supplied the pilot in a simple display showing relative positions and spacings on the common track.

If the positions tend to close so that the gap between consecutive aircraft is shifted unduly, it becomes apparent to all the pilots involved. The rate information commanded by ATC as a common track speed for all aircraft is used in turn to re-establish the spacing. If, for example, a given aircraft is not spaced at a nominal 5 miles but is spaced 4 miles from the "fore" aircraft and 6 miles from the "aft" aircraft, a slight reduction in speed will re-establish the desired 5 miles. The track speed is in terms of the differential track coordinates, and the track spacing is in terms of the differential track coordinates, so that all adjacent aircraft utilize the same information base for spacing. The ground monitoring of the LOP roll-calls also uses this common information base. Figure 23 illustrates the displays and pilot participation in this concept.

L. IMPACT OF NEW ATC COORDINATES FOR BROADCAST CONTROL

What we have postulated above is quite revolutionary in the area of air traffic control concepts. Today the ATC information flowing between ground and air and the related need for so many controllers is premised partially on the fact that the pilot does not have track rate, high quality tracks, nor spacing information, nor is it planned to give it to him. Some have proposed giving similar information to the pilot via a data link on the SSR 1030-MHz channel used as an "up-link." This violates our intent here that we want to reduce the load on the ground computation and human surveillance and provide more pilot-oriented information. The SSR ground computation of this rate information and discrete commands to each aircraft will require enormous extra costs and burdens on the ground system. The SSR is heavily loaded now and serves a complementary surveillance function, but



FOUR BASIC ATC ELEMENTS FOR ADDED CAPACITY USING BROADCAST CONTROL CONCEPTS AND DISPLAYS FOR PILOT PARTICIPATION IN ATC OPERATIONS

FIGURE 23

it would be a poor "close-control" means for many reasons. The use of a superior navigation system suited to ATC "broadcast" concepts will avoid this overdependence on SSR.

Again it is due mostly to the 10:1 discrepancy between SSR and VORTAC accuracies that leads the ground-oriented system designer to prefer data link control of the aircraft—something that will further remove the pilot from his essential place in the ATC control loop. Since pilots have little voice in ATC operation and planning, and electronic engineers predominate with leanings toward more ground electronics and computers, the pilot's view of ATC is not emphasized.

It is not the intent here to design a new "strategic" or "broadcast" type control system except to substantiate the fact that technology that is already well proven can quickly be applied to providing such a system. It does mean, however, an overhaul of the basic positioning system that has been used for 30 years; however, VORTAC should not be eliminated, but it could serve in considerably fewer numbers as a backup system. This new concept can be exploited by developing more economical airborne electronics and displays and by giving pilot-oriented concepts much more credence; something that entails many political problems.

Fortunately, most of the new Area-Nav computers of the airlines will accept long baseline inputs as well as VORTAC's multiple, polar-coordinate inputs, so that only the aircraft's navigation receiver need be changed. In fact, from a computation view in the air the contiguous wide area, oblique-parallel or rectilinear type (LF-VLF) coordinates are far superior to intermittent small area polar coordinates which require slant range corrections. Not only is computation simpler, faster, and geometrically more suited to ATC, but the inputs are about 10 times more accurate. No computer can compute for its output anything of better quality than its inputs. The modern, high accuracy, digital computer is hardly warranted with VORTAC because of serious input limitations; yet, it would be put to good use with the precision of the wide baseline VLF and LF systems.

Certainly mixing of heading and aircraft attitude in the pilot displays will be essential; however, this is an old and well known practice not reviewed here. What is lacking in ATC is a new, more solid foundation to build, one which is more likely to be obtained with long baseline LF/VLF systems than with VORTAC.

It is not possible to predict the detailed outcome of a successful changeover to the new coordinate system and broadcast control herein suggested, but it is possible that the growth projections for ground ATC personnel could be reduced by a significant fraction by shifting many of the ATC functions into the cockpit. Since payrolls seem to increase forever, even a saving of 10% of the predicted number of controllers and maintenance staff needed with VORTAC and close control ATC concepts would mean a saving of thousands of additional FAA employees. Only 10 LF or VLF stations would be needed to replace the over 1,000 VORTAC stations.

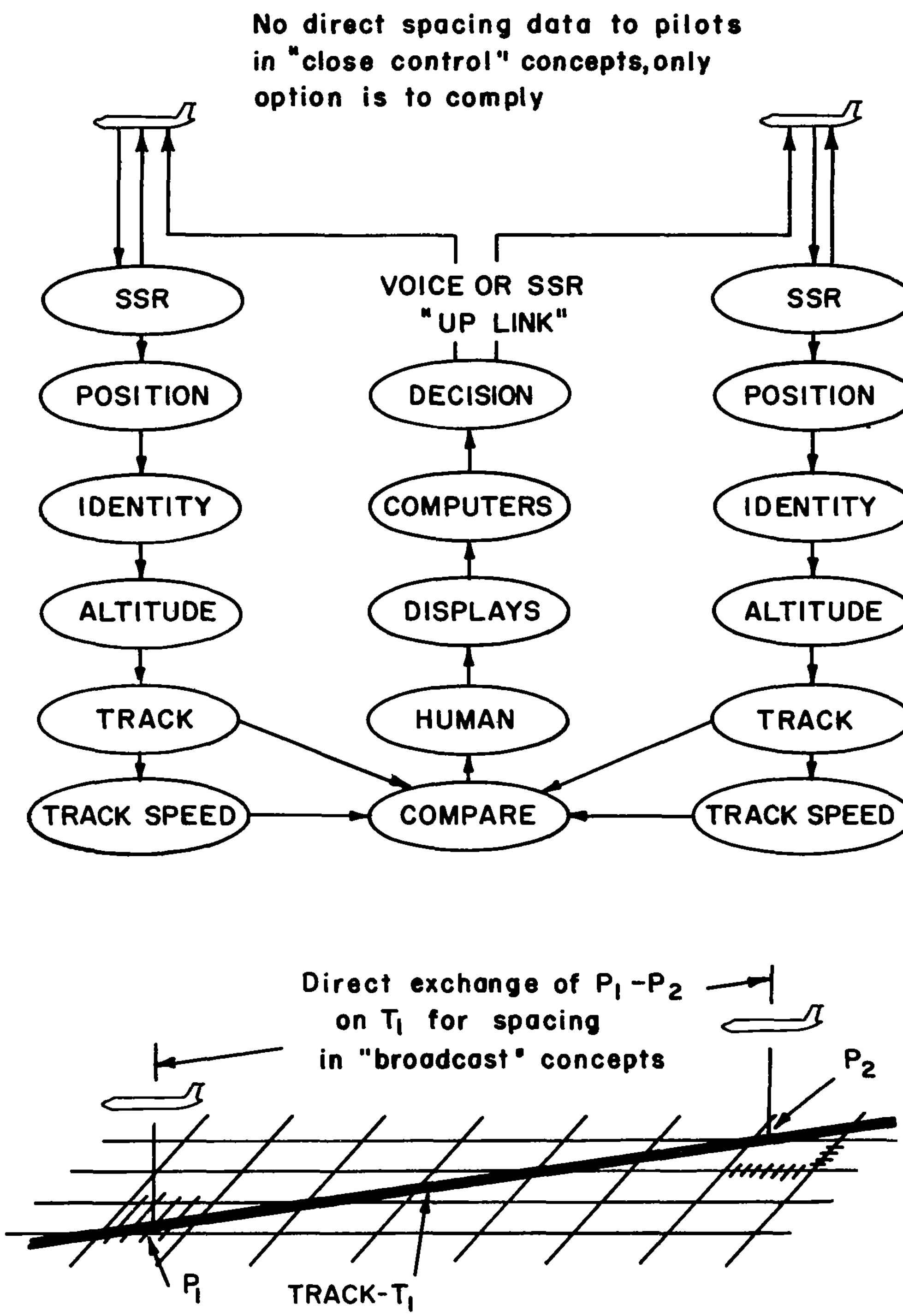
The future costs of VORTAC and its modernization, requiring both new ground stations and new receivers to obtain improved VOR data using PVOR, is a major national cost since ultimately hundreds of thousands of new receivers may be required. Even after costly modernization, most of VORTAC's constraints on the entire ATC process remains for the many reasons cited previously, such as poor geometrics, lack of contiguity, and angular divergence. Research on VORTAC's replacement should be greatly accelerated now as the savings could be far greater than has been suggested. The cost of about 20 billion dollars per decade for only the FAA part of running the ATC system must be reduced as ATC may well "price itself out of business" by the end of the decade. Personnel costs will be about 1 to 4 billion dollars per year out of a 2 billion dollar FAA total during the '75 to '80 period, or 70% of the total.

M. SUMMARY OF ATC INFORMATION EXCHANGE BETWEEN CONTROLLERS AND PILOTS

It is obvious that improved pilot participation in specific functions is one of the most important areas in increasing the capacity of the ATC system and for reducing what may be prohibitive costs for ATC services. It can and should be fully researched. Specific pilot participation is also very obviously an "air-oriented" concept rather than a "ground-oriented" concept. We wish to restate here that it is the optimum balance of these two "orientations" that makes for success in ATC, and that the imbalance that now exists favors the ground-oriented views. Many plans are built around this concept of ATC, and most industry plans are directed at increasing this imbalance (such as the ATCAC report on the complex data link to the pilot commanding him what to do instant by instant). Pilots and aeronautical (air-oriented) system planners must exploit the "broadcast" concepts of ATC for specific objectives, such as common-track spacing, that are better suited to cockpit control as is shown in Figure 24.

Since the FAA operates and maintains all ground facilities and no user aircraft, it is predominantly oriented toward the ground solutions, and its budget, personnel and recent progress reports and projections attest to this. The ATCAC report prepared by many FAA participants further emphasizes this ground-oriented ATC view.

The pilot and the air-oriented concepts do not have champions who are in equally suitable positions for exploiting the broadcast-cockpit concepts and testing their merits for improving ATC capacity and reducing costs. Furthermore, the safety of ATC should be greatly enhanced by these air-oriented concepts, since the air-to-air pilot usage of spacing and track speed data adds the pilot to the ATC control loop. He is best suited to direct spacing control between other aircraft, and then a collision avoidance system is not required as such. Perhaps a proximity alerting signal is required using SSR as a



CONTROL OF COMMON TRACK SPACING IN SIMPLIFIED
CONCEPTS OF "CLOSE" AND "BROADCAST" CONTROL

FIGURE 24

redundant signal beyond the VLF-LF coordinate and roll-call systems to provide this extra pilot assurance.

We must now determine how this concept is best evaluated and exploited. Since it involves the aircraft directly, as well as the pilot and his new displays, the "air" concepts must coordinate the ATC functions of pilot and aircraft. This pilot-broadcast control concept of ATC is an integral part of the meaning of aeronautics. It is essential that those agencies in the government skilled in the predominantly aeronautical solution and skilled in pilot-oriented disciplines should be deeply involved in the air concept development. This strongly suggests that NASA be encouraged to exploit this new ATC concept from the air-oriented view. NASA's history and resources closely match the needs for exploiting this new concept of ATC, where the flight dynamics, aeronautics, and pilot's functions are far more favored than at present. Considerable research is needed as well as validation testing, simulation, etc., of the ideas for this new "broadcast" or "strategic" concept of ATC.

However, the R & D costs for this concept will be only a small fraction of the potential savings in manpower and hundreds of ground facilities. Since we are talking about billions in potential savings over the coming two decades, it is warranted that national emphasis be placed on this concept by an agency that is naturally aeronautically oriented, such as NASA. An early indication of its potential can be realized in a year or so with an intensive air-oriented pilot, display, and flight control program using already existing signals of Omega and Loran-C. If the concepts are clearly proven, the implementation of some LF-VLF coordinate systems superior to both Omega and Loran-C can be readily engineered with the vast knowledge now available in this field. Similarly, the volumetric microwave guidance system can provide close-in precision for pilots using these coordinates for multiple-runway jetports.

It is likely that the expansion of "close-control" ATC concepts must be abandoned in time, and balanced with expanded broadcast control. Since the failure to gain additional capacity by overdependence on "close-control" cannot be exactly predicted and is somewhat in the future (as are the enormous expenditures for thousands of ground controllers and more VORTAC facilities), it is not easy to convince responsible authorities to plan R & D on an urgent basis for these pilot-oriented "broadcast-control" concepts. The general aviation user will also benefit from this plan, and we will discuss these aspects separately so as not to confuse the sophisticated airline and military piloting and ATC problems (in dense terminal areas) with those of general aviation. The coverage of the nation with a uniform grid of guidance data at all elevations (including runway surfaces) will allow dispersion of general aviation traffic and airports. VSTOL airports away from the congested areas will also gain considerably. At present, the only locations that have full altitude coverage and/or accuracy using VORTAC are the congested areas. Airport and VSTOL dispersion cannot take place unless ATC facilities are provided.

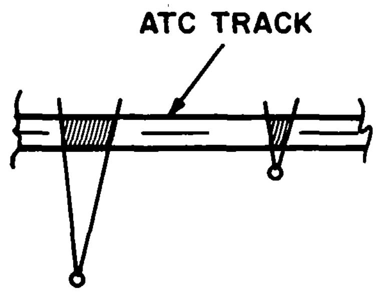
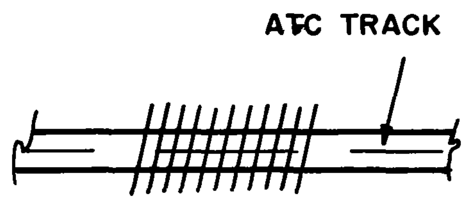
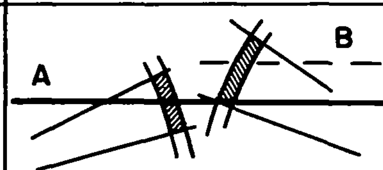
By providing the cockpit guidance accuracy, track spacing and track speed control capabilities that are complementary to those of the ground SSR computers and controller displays, a true balance is effected between the only two persons who are of any consequence in ATC: the pilot and the controller. No manner of regulatory procedures will improve a relationship that has not been supported by good electronic facilities for ATC. The pilot with new electronics will then be as valuable to ATC's future growth and capacity as the controller, yet each will serve in his own right, and engineering will provide the wherewithal to carry out their legal responsibilities.

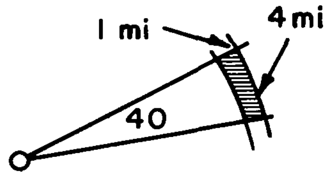
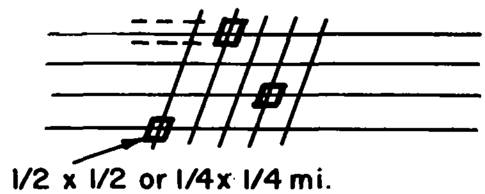
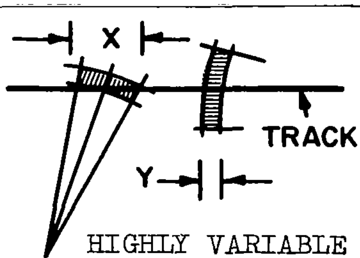
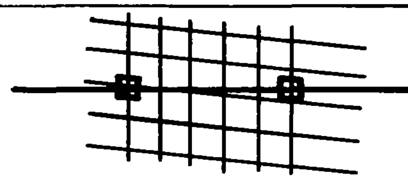
The aeronautics, displays, pilot testing, simulation, and the entire interface of all the airborne units that go to make broadcast control an ATC success need a centrally directed research and development effort that is strongly aeronautical or air-oriented. The inability to realize national ATC improvements because the sponsors or developers are essentially ground-oriented in their ATC concepts must be overcome. This suggests a priority assignment to NASA's major research centers, such as Langley or Ames, to undertake this vital research in cooperation with the electronics effort of DOT's Research Center.

Table IV summarizes many points covered in this section and previous sections.

TABLE IV

COMPARISON OF SYSTEM CHARACTERISTICS
OF VORTAC AND LF/VLF

SYSTEM CHARACTERISTIC	VORTAC (Area-Nav)	LF/VLF (Wide Area-Nav)
TRACK SPEED MEASUREMENTS	 VARIABLE AND LOW	 UNIFORM AND HIGH
AIRWAYS USING MULTIPLE STATIONS	 POTENTIAL FOR MISALIGNMENT DUE TO DIFFERENT ERRORS IN SWITCHING STATIONS	CONTIGUOUS COVERAGE AVOIDS THIS SERIOUS ERROR AS ONE THOUSAND MILE BASELINE STATIONS (4 of them) PROVIDE COVERAGE OF HUNDREDS OF VORTACS
LONG TRACKS USED IN ATC SCHEDULING	VARIABLE GEOMETRICS VARIABLE ERRORS STATION TO STATION ERRORS FORCE ATC TO ASSUME WORST ERRORS IN USING TRACK RATE	CONSISTENT ERRORS AND CONTIGUOUS COVERAGE ALLOWS LONG TRACKS WITH GOOD RATE CONTROL IN EACH AIRCRAFT FOR HIGH TRAFFIC FLOW AND CAPACITY

SYSTEM CHARACTERISTIC	VORTAC (Area-Nav)	LF/VLF (Wide Area-Nav)
NUMBER OF STATIONS FOR CONTIGUOUS U.S. (to low height)	BETWEEN 1,000 to 2,000	LESS THAN 10
GEOMETRIC SHAPE AND SIZE OF ERRORS	 4 Square Miles at 40 miles	 1/16 to 1/4 square mile at 40 or more miles
ORIENTATION OF ERROR GEOMETRICS WITH ATC FLIGHT TRACK GEOMETRICS	 HIGHLY VARIABLE (X and Y) ALONG TRACK ERRORS	 CONSTANT ALONG TRACK ERRORS
POSITIONING ACCURACY FOR ATC TRACK CONTROL	DEPENDS ON VORTAC LOCATION RELATIVE TO (1) AIRCRAFT AND (2) TRACK DESTINATION VARIES FROM GOOD TO VERY POOR	CONSISTENTLY GOOD AND INDEPENDENT OF LOCATION OF AIRCRAFT AND DESTINATION

SYSTEM CHARACTERISTICS	VORTAC (Area-Nav)	LF/VLF (Wide Area-Nav)
NATURE OF TOTAL NATIONAL COORDINATES USED FOR ATC AND GUIDANCE	Over a thousand randomly spaced and oriented, polar coordinate diagrams, not organized on a national coordinate plan, with variable quality service, requiring complex coordinate transmission and processing for dual station use	A uniform, contiguous coordinate grid on a national basis with uniformly good service
THREE-DIMENSIONAL COVERAGE	Poor or unusable coverage at low altitudes for letdowns to thousands of remote fields. Inadequate in mountains, valleys, due to multipath transmissions or line of sight	Coverage to and on the surface in all types of terrain
QUALITY CONTROL	Must inspect continuously over 1,000 stations as local reflections and individual stations can have flight errors, even with monitoring of each station. A very costly, quality control system	Minimum flight inspection and ground monitoring correlate better due to propagation characteristics. Total quality control and assurance is much simpler at much lower costs
COMPARISON TO ATC SURVEILLANCE	SSR ATC ground surveillance is about ten times better, forcing more ground-controlled concepts of ATC and limiting pilot participation in ATC	Granularity and accuracy matches those of the SSR system (about ¼ to ½ square mile each), permitting increased pilot participation and responsibility in ATC
USE IN "BROADCAST" OR "STRATEGIC ATC CONCEPTS	Uncontrolled errors and geometrics vary along track preventing broadcast use. 10:1 lower resolution than ground surveillance system which will monitor broadcast	Appears ideally suited as accuracy and contiguity of coordinates allow on-board track speed and spacing measurements, both vital to broadcast ATC concepts

SYSTEM CHARACTERISTICS	VORTAC (Area-Nav)	LF/VLF (Wide Area-Nav)
AIR-TO-AIR TRACK SPACING IN BROAD-CAST CONTROL	Coordinates unsatisfactory for close spacing between aircraft on a common ATC track since ATC must as-sume "worst-case" accura-cies for spacing	Coordinates allow several simple methods of air-to-air (cockpit) information for direct track spacing in broad-cast control
SUITABILITY TO "SLANT" OR "SLOPING" AIRWAYS	Poor since positional error creates vertical errors; must also be "slant-range" corrected	Good since contiguity accuracy and error "geometrics" add little vertical error; no need for slant range correc-tions
COST TO NATION PER DECADE	High, requires major changes in hundreds of VOR and DME's for future air traffic loads with large maintenance and monitoring costs persisting. Over 100,000 aircraft units will be replaced	Much lower (possibly ¼ or ½ of VORTAC) with savings over a decade or two of utilization in billions of dollars
SIGNIFICANT PROBLEM AREAS	°Channelize to 50 kHz °Add new PVOR signals and stations °Change most airborne re-ceivers °Some re-siting °Enormous maintenance and quality control °Many more stations to ob-tain low altitude coverage °DME channels limited °Limited technology base	°Effects of atmospher-ic and other elec-trical interference °Diurnal change if VLF is used °Big stations
STATION COORDI-NATES FOR ATC	°Station elevation °Station coordinates in "lat-long" as well as station identity must <u>all</u> be transmitted on each station (not now trans-mitted) °Differential, dual-station coordinates must be com-puted in air	One common set of coor-dinates with continuous cover of hundreds of separately referenced VORTAC's

SYSTEM CHARACTERISTICS	VORTAC (Area-Nav)	LF/VLF (Wide Area-Nav)
SECTORIZATION OF ATC	More and smaller sectors needed since surveillance takes on part of track guidance and spacing functions	Fewer and larger sectors; geometrically more satisfactory sectorization since 1.Area track guidance, 2.Track speed, and 3.Spacing information are in cockpit
NUMBER OF CONTROLLERS FOR GIVEN NATIONAL ATC CAPACITY	More	Fewer
POTENTIAL FOR PILOT PARTICIPATION IN ATC	Less	More

VI. NASA UNIVERSITY PROGRAM IN AIR TRAFFIC TECHNOLOGY

A. INTRODUCTION

Several recently completed studies and reports relating to the nation's aeronautics and air traffic control problems have indicated that major steps must be taken in a few short years if aviation is to continue to play the major role expected of it in the nation's economy and transportation system. Civil aviation growth is threatened by frequent saturation of the current ATC systems, lack of adequate, scientifically designed airports, and by its increasingly poor relations with the surrounding community. The several reports by the (1) National Academy of Engineering, (2) the ATA (ATC report of July 1969), (3) the Alexander Committee (DOT) report of February 1970, and such reports on congressional hearings as (4) "Aviation Facilities Maintenance and Development, September 1969, and (5) "Aeronautical Research," December 1969, emphasize the need for major improvements in ATC systems and the complexity of the undertaking.

We are formulating through these committees and studies a national program in aeronautics that, though basically civil in nature, has DOD overtones since a "common" system is more in the national interest wherever practical than separated or non-cooperative civil and military systems. Advances in aeronautics become more and more related to radio navigation, air traffic control, airport design and surface control, and improvements in the relationship of aeronautics and the community--be it noise, economy or safety. Recent major commitments to a vast new fleet of jumbo jets has effectively dictated that these problems be solved.

B. AIR TRAFFIC CONTROL

R & D activities resulting in total expenditures from 5 to 10 billion dollars during the decade of the 70's is typical of cost estimates. The civil portion alone may result in an

FAA staff of over 80,000 persons by the end of the decade. Of this total it is estimated that some 43,000 persons will be air traffic controllers. Billions will be added to the existing high airport investments in an effort to provide suitable airport capacity. The solutions to airport problems are far from simple civil engineering matters, with traffic capacity determined more by the results of operations research, taxiway design, parallel runway spacings, and extensive electronic aids (detection-loops, ASDE, computers, pilot signalling, etc.). Aircraft instruments for Area-Nav, collision avoidance, altitude reporting, data link and automatic flight control are an additional major multi-billion dollar market during the '70's. New flight control concepts and pilot displays are essential for curved flight and low-visibility landing.

Thus, whether the national investment is in cockpit instruments, aircraft, people, airports, or electronics, the "total" system is so interrelated that a basically new "total-system" approach must be taken. This is perhaps the most sophisticated type of engineering and scientific inquiry, since it involves high level technology, economics, legal, regulatory, and other aspects not usually contained in the background of system engineers.

The question naturally arises as to where all the needed professionals will be trained to research, design, manufacture and execute this massive new national program. Little in the way of organized education programs at the Bachelor, Master, and PhD levels exists in the United States at this time that is commensurate with this forthcoming demand for trained technological professionals. Furthermore, there are many well educated personnel in government agencies that will be required to carry out the R & D and implementation of this national plan; this will require extensive re-training in these new sophisticated areas. Many trained in the space sciences, for example, may be re-trained in the air traffic sciences as increased responsibilities are assumed by the various agencies and industries in this national effort.

Modern ATC subjects are complex and interdisciplinary, involving many of the basic sciences (as applied to aviation), such as electronics, civil engineering, mechanical engineering, operations research, economics, the law, aerodynamics, and many more. A student desiring to become educated in this new and attractive area will be hard pressed to find a university that can provide the breadth of course material and research opportunities needed. Much new course material and an expansion of the teaching staff are required to obtain the knowledge the student needs to work effectively in the national ATC associated aeronautics program.

C. THE SELECTION OF UNIVERSITIES FOR THIS STUDY

Although other universities teach related subjects, it was determined by the author that only four universities are at present deeply involved in the areas related to air traffic guidance and control. Each of these universities has a small, well-established research and educational program in this field. Taken as a whole, with the exception of certain areas, the four universities we will discuss do not overlap in ATC interests but are quite complementary. The cumulative interest of the four tends to cover the spectrum we are concerned about in the national ATC-Aeronautics problem area. Fortunately, each of the universities is represented by an outstanding professor well-versed in the aspects of ATC-Aeronautics. Each professor is not only at present involved in the various aspects of the national ATC program, but is also actively teaching and advising candidates for Bachelor, Master, and PhD level degrees in these ATC-oriented technical areas.

Admittedly, what one might refer to as the "production" of professionals in these areas is now at a low annual rate. Although not fully estimated for the forthcoming major national ATC undertaking, it is possible to immediately encourage these existing programs and to increase the number of graduates from this current base. We will discuss each university's program, their interrelationships, and the methodology for accelerating the supply of these types of graduates. One must anticipate this coming demand for professionals trained in ATC technologies as the time involved per student will vary from one to five years, with an average "lead" time of three years being typical.

D. UNIVERSITIES NOW INVOLVED IN ATC RESEARCH, TEACHING, AND DEGREE GRANTING

Under the limits of this NASA contract (NASW-1849), it is impossible to review the total national educational system with respect to ATC and Aeronautics. It was possible, however, to select the few representative universities who have a proven record in producing Bachelor and graduate degree students related to ATC. Since the nature of ATC technical activity requires the involvement with many agencies, committees, and professional societies, it was possible to identify the key professors and the universities involved. The professors assisting the author are: Professor Horonjeff of the University of California's Institute of Transportation and Traffic Engineering; Professor Richard McFarland of the Ohio University College of Engineering, EE Department, and head of Avionics Research; Professor Robert Simpson of MIT, Department of Aeronautics and Astronautics and Director of the Flight Transportation Laboratory; and Professor Dunstan Graham of Princeton University's Flight Sciences Section of the Department of Aerospace and Mechanical Sciences.

Each of the universities is involved in a slightly different way in the ATC and Aeronautics program areas. These universities were considered in this study because of the diverse, yet complementary, aspect of their interests and because of their broad experience in educational programs in the ATC-Aeronautics areas. The breadth of interest typifies the ATC area and is of greater value than redundant interests. By conferences at each of the universities and a one-day conference at Headquarters NASA (3/12/70) it was possible to identify the programs at each university and to examine them as to their value in a possible NASA University Program in ATC (and related aeronautic-airport subjects).

For example, Professor Horonjeff's experience (at the University of California) in the airport research area includes the preparation of several basic studies using a "fog chamber" to test runway lighting for CAT II landing operations. The 1,000-foot-long facility permits a highly controlled visibility (fog) to be created, so that a pilot viewing the approach and runway lighting systems (as he descends on a 2½° track in an aircraft cockpit) can determine his ability to obtain the essential visual cues to complete the landing at the "decision height" by purely visual means. Since all (but one) landing authorizations include this final, visual phase (even those highly electronic, non-visual-dependent to the decision height), the transition to visual "see-to-land" is most important to safety.

Successful Master and PhD thesis work has been completed at the University of California in connection with these problems and in technical areas related to the geometric design and surface traffic control aspects of airports. Several other related programs and thesis work have been completed on ATC delays related to interactions between surface and final approach, traffic, terminal buildings, and designs of jet airports. Since major investments in taxiway, runway, and electronic surface control systems are under way throughout the nation, the scientific approach to these airport programs to maximum safety and traffic capacity, there is an increasing demand for graduates at all levels. Professor Horonjeff's book, Planning and Design of Airports, is employed in teaching throughout the country.

Professor Simpson's (MIT) Flight Transportation Laboratory goals are in the areas of Flight Vehicle Technology, Airport Design and Operations, Flight Transportation Systems Analysis and Planning, Navigation-Guidance and Air Traffic Control. The programs in Flight Transportation are at the graduate level. Aeronautical, Civil, Mechanical, and Electrical engineers have successfully participated in these MIT programs. Both the Masters and PhD degrees are awarded based on a program chosen by the advisor and student and approved by the associated faculty. The Masters program can usually be completed in about two years, and the PhD program usually requires more than 3½ years of graduate studies.

These individually structured programs draw on the courses taught at the various schools at MIT, such as the school of Management, the Operations Research Center, and at Harvard. Professor Simpson, for example, plans to expand the course material in areas such as Air Traffic Technology in the coming year. Typically, a Doctoral thesis may include basic theory of ATC concepts, such as a recent one entitled, "An Analytical Investigation of Air Traffic in the Vicinity of Terminal Areas," December 1969. In this PhD thesis an analysis is made of the effects of aircraft spacing, velocity, runway assignment, etc., using various modeling techniques related to airport and airspace capacity. Flight research work is accomplished at MIT using aircraft based at Hanscom Field, wind tunnels, and computer facilities.

Professor McFarland (Ohio University) has established courses that are taught at graduate and undergraduate levels relative to electronics and radio associated with aviation. This technology is often referred to as "avionics." In addition, a large group of about 20 professors, associate professors, and graduate students are involved in research work in such areas as VHF/UHF landing facilities, investigations of VOR errors, aircraft antennas, VLF systems for light aircraft, and means for improving the monitoring of the ILS system. Flight research work is often done using the University's DC-3 Flying-Laboratory or in smaller aircraft. Thus, laboratory work and flight tests are associated with the university's program in Avionics. The support for this graduate work comes from grants or R & D contracts with such agencies as the FAA, industry, and the Army Electronics Command. Several successful results have been forthcoming from research conducted for these agencies, and improvements in certain ATC facilities have been made. Flight facilities, such as a small airport at Athens, Ohio, large towers, and mobile field laboratory vehicles, permit this type of research to be conducted at various ground test sites in the proximity of the university. Both Master and PhD degree programs are provided by the University in these technical areas.

Professor Dunstan Graham (Princeton University), his associates, and graduate students are more involved in the areas of aircraft instrumentation, pilot displays, and flight control. The many problems associated with the utilization of information in the cockpit of an aircraft by the pilot, such as landing guidance, navigation, displays, flight controls, stability and control, etc., are addressed in this research. Princeton University maintains a well-staffed hangar and several aircraft at the Forrestal campus to conduct this research. The graduate students are deeply involved in these projects, and the research results are often used in both Master and PhD degree programs. Emphasis on VSTOL aerodynamics, instrumentation, guidance and control has been increasing in recent years, and an extensive research effort in this area with ECOM (Army-Avionics Laboratory) has been under way for the past few years.

A variable-stability aircraft has also been developed at Princeton for the Navy and is the basic tool for flight simulation and carrier landing studies. Characteristics of various types of aircraft can be electronically simulated in actual flight with this single aircraft, helping in the assessment of such problems as the precision of flight following of visual and electronic landing aids for carrier landings. A facility utilizing a long track to investigate the flight properties of a variety of scaled VSTOL aircraft is also available. Professor Graham (as others do) is actively engaged in consulting for industry and government to stay abreast of the technology and the demand it places on technical education.

E. COMPLEMENTARY NATURE OF THE PROGRAMS AT THE FOUR UNIVERSITIES

From the above abbreviated description of each university's program, it is obvious that little overlap or duplication exists between the four universities in their research programs and course materials. It is also evident that some important areas of ATC technology are not covered by these programs. However, the total programs admirably serve to demonstrate an existing, on-going university program in the aeronautical sciences closely tied to

Air Traffic Control technology. It was obvious from the Washington conference, which was attended by NASA and the universities, that the ideal student product might be a graduate that had completed coordinated course and research work at all four of the universities represented in this study. However, this is not too practical at present, but it does suggest that because of the breadth of the special disciplines that make up a total national approach to Air Traffic Control technology (and its impact on aircraft, airports, the community, the public safety, and economy), some cooperation between at least pairs of universities would be beneficial.

At least initially, there appears to be more of a common interest between the University of California and MIT's programs because of many past interchanges and working relationships of the professors and staffs involved in similar programs. Similarly, it appears to the author at least that Princeton and Ohio Universities have some common interests in Avionics used for navigation, guidance and control, as both the ground facilities and the aircraft displays (instrumentation and control dynamics) are related. Obviously, for the most broadly trained individual, even a combination of the two pairs would be most beneficial, since the many interfaces of "total-system" engineering that are so vital to the nation's ATC problem include the vehicle, electronics, and the airports. The required "total" system exposure is typified by the areas represented by the four universities.

It is fortunate that we have this spectrum of the ATC technology so well demonstrated in the course and research content of the four universities. It was the view of most of those present at the conference that this on-going program could serve in one form or another as a foundation to build on, so that expanded numbers of graduates and more course material would become available by means of some form of government assistance. It is also obvious that other universities have programs of merit but that because of the limitations of this study, and the logistics involved, it appeared that a "hard-core" program started with the four universities represented could be expanded by NASA to other qualified universities if and when warranted. There is a possibility that a fifth or even a sixth university program ranks along with the above four. It is not the intention here to eliminate any participation but to stress the need to select those universities that are already deeply involved in ATC technology and that have the experience of a few years to assure an initial success of a NASA-ATC technology university program.

F. GENERAL OUTLINE OF A POSSIBLE NASA/UNIVERSITY PROGRAM IN ATC TECHNOLOGY

As ATC is defined here it includes , in the broadest sense, the airport, vehicles, ground and air electronics, pilot instrumentation, flight dynamics, legal aspects, economics, management, etc. ATC is used to identify this large area of Aeronautics and to avoid misunderstandings as to inclusion or exclusion of other on-going programs in space, advanced aeronautical vehicles, propulsion, etc. By encouragement of the universities now active in the ATC areas, it would be practical to increase the number of degrees granted at Bachelor, Master, and PhD levels in the next few years. This encouragement can come in one of several forms and we will discuss one mechanism, the research grant, that received considerable attention at the conference. However, it was emphasized by most present that the current interest emphasizes an increase in the number of Master degrees per year rather than an increase in PhD degrees. On the one hand, the complexity of the technology often requires more training than a Bachelor's degree in many instances. On the other hand, there seem to have been (by recent estimates) too many PhD level graduates. Thus, the aim might be to satisfy all levels, but to stress the Master level program. This has advantages for filling the expected demand in ATC technology as needed professionals can be available in less time from the university for employment in industry, government, and elsewhere. This will aid in the solution of the innumerable ATC-associated problems that are envisioned to be increasingly evident during the 1970-1980 time period.

Admittedly, if one looks at the immediate present needs for this talent they are not high. Yet, the planning of major systems on a national basis for design and implementation during the '70's cannot be realistic without qualified professionals to execute the plans. Thus, one cannot measure the true demands by the small current demands (particularly in an area that is identified as technologically deficient). It is possible that the lack of professionals with better educational backgrounds has precipitated this national concern about the gross inadequacies and crises in store for the national ATC system. Because of inevitable delays, a three-year anticipation of demands for such graduates must be recognized. To measure the need for such professionals in ATC technology by past standards is merely to suggest that we are willing to accept about the same consequences.

Thus, if one is to stand back and take an overview of the national programs and the enormous expenditures (by past standards) that will be essential to add ATC capacity and to modernize the nation's ATC system, engineers with much better backgrounds and in greater quantities than those presently involved must be available. Some professionals can be re-trained in many cases, and this may be a second important avenue to follow. However, a far more basic method is to attract the bright young student before he is committed elsewhere and to start him in a career related to aeronautics and air traffic technology. The current student preference for solving major civil problems and avoidance of military programs should assure most university personnel that the source of qualified students will be large. Once such a program as herein discussed is under way and publicized, a wide selection of the best candidates can be made. Future employment would be in the research, design and implementation of major new systems, such as the RTCA SC-117 system (new microwave landing system), the "Super" Beacon system of the Alexander report, "STRACS," major new flight instruments (such as Area-Nav, curved-linear flight following, automatic landing, etc.). These are but a few examples of some six to ten major new systems that must be designed, tested, validated, and implemented, but that do not exist today. Each system can cost from 300 million to 2 billion dollars, depending on the nature of the system and the number of national installations (air and ground) that will be involved. The magnitude of these expenditures is so great that one cannot tolerate the possibility of technological failure. A far more "scientific" approach to these systems is required than ever in the past.

Since most facilities (ILS, VOR, DME, radars, SSR) are now from 20 to 30 years old, it is the skillful application of new technology that supplements the old and creates major capacity increases that is essential to cope with national projections of air traffic. Even more difficult system planning is needed as each major system cannot be developed in isolation from the others. The "total-system" composed of the many major elements that will cost several billion dollars (over 1 to 2 decades) to accomplish requires talents not now available in adequate supply.

Thus, it is projected that as the major overhaul, expansion, and modernization of the overall ATC system (electronics, vehicles, airports) gets under way, the demand for engineers and scientists specifically trained in the aforementioned disciplines will outstrip anything now envisioned. Just as NASA aided the universities in the space program and created a needed large supply of new graduates at all levels trained in the space technologies, so we need in about 2 to 3 short years an ever-increasing supply of graduates trained in the aeronautics and air traffic technologies. It is likely that nearly any incident can trigger a much larger national effort to modernize the ATC system and to expand it--for example, a continuation of mid-air collisions, a landing accident of a jumbo jet, or economic chaos due to airport and air traffic saturation. It is the objective here to identify and plan an initial, basic university program in ATC, starting in the near future, to satisfy this forthcoming public demand for better solutions to the large civil system problem.

The existing facilities will continue to operate for some time, and the FAA has a major program for their expansion and modernization. Even in this area, much modern technology should be applied rather than simply installing more of the same limited devices. Major improvements in VOR, for example, suggest that its accuracy can be enhanced for Area-Nav (AC 90-45). Consequently, we have a parallel need for the expansion of current facilities and to utilize them more efficiently (siting, channelization, information content) in airspace assignments. However, there will be a most difficult engineering task ahead. Adding capacity to the existing total ATC system by supplemental and compatible systems, such as the SC-117, VLF guidance control, new transponder codes, airborne displays and flight control devices, etc., must be done without removing or disturbing the older systems. The compatibility of the "old" and "new" is important, as ATC differs from other single-purpose systems (straight line management such as Appollo, Air Defense, etc.).

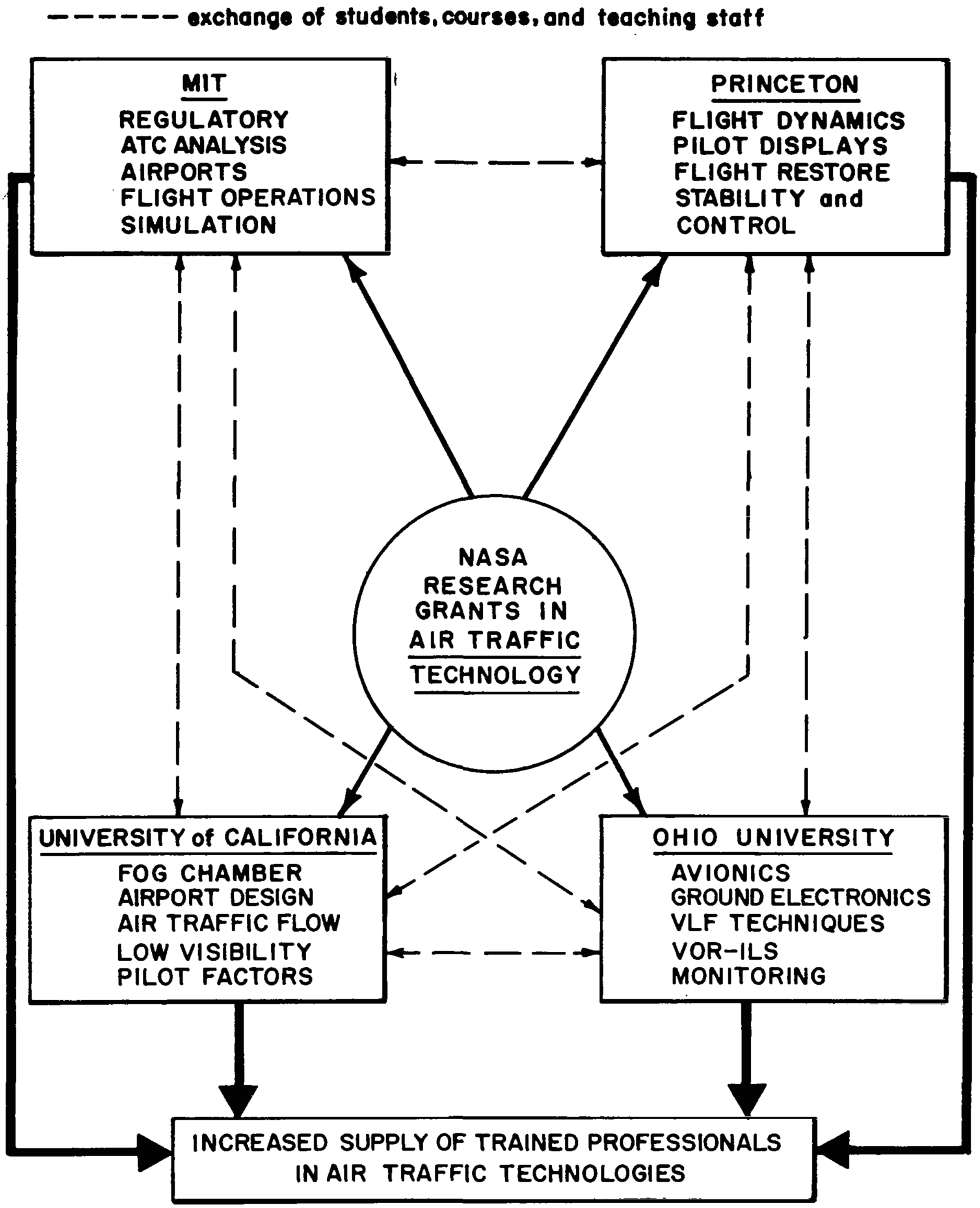
Many "system" experts are familiar with what are basically simpler problems. ATC technology is the most complex of system engineering challenges: to assure enormous additional capacity with selected technology, while not disturbing or destroying the operational "on-line" system. In the case of general aviation (light aircraft) this capacity must be added at greatly reduced costs compared with past modernization efforts. Although the owner of a 20-million-dollar airliner can accept 500 thousand dollars of ATC related electronics, a 20 thousand dollar general aviation aircraft owner cannot. Yet, for public safety he must not be deprived of commensurate facilities suited to his environment and aircraft for, say, about 3 or 4 thousand dollars. This is an enormous technological challenge not faced by anyone on a large scale at present. It is obvious that such a complex total system will require the best brains of the nation trained at the best universities to prepare them for the planning and engineering of such systems that offer a magnitude of operational improvements but at a magnitude of lesser cost.

G. METHODS FOR NASA/UNIVERSITY SUPPORT

A 1968 report, "A Study of NASA University Programs," outlines several means that NASA has employed in the space program to assist universities during the past decade. Although some Aeronautics was included, this university program was predominantly oriented toward space, while the program herein discussed is primarily oriented toward ATC technology and associated Aeronautics. The magnitude of the ATC program will be considerably less than that of the space program; however, it may well be necessary to provide long-term support if the objective is to create the quality and quantity of the much needed new talent in the air traffic technologies. The air traffic areas requiring support will be more specific, and some of the broad justifications for space university programs would not be needed.

Basically, the "Three-Year-Stepped-Funding" type of research grant seems to be the best method to consider rather than other methods employed by NASA in past university programs. Most of the reasons for this assumption are complicated, and many were discussed at the 12 March, 1970, conference. However, funding can be a secondary matter, once a joint understanding is established between NASA and the universities in the air traffic technology areas. Figure 25 notes the wide scope of the technical areas. Again, air traffic is a term used to identify the type of university program intended to avoid confusion with other on-going vehicle programs.

Utilizing this step-funding mechanism, a research proposal is prepared for a research grant by the universities. If accepted, it is then funded fully for the first year, 2/3 for the second year, and ⅓ for the last year. This avoids any precipitous cancellation and permits the university to attract and execute the type of research (performed by graduate students in most cases, but supervised by a professor) herein envisioned. Typically, a 100 thousand dollar a year effort will support about 8 to 10 students at the graduate level depending upon the equipment or materials needed. Other facilities that may be involved



SCOPE OF TECHNICAL AREAS

FIGURE 25

in the research effort also affect this figure. Such a level allows enough graduate students at a given university to become involved so that additional course material can be generated and taught. Such aid further attracts professionals into the university to supplement and/or add to the existing limited teaching staff. The universities (herein discussed) are generally having trouble obtaining qualified staff for teaching or supervising the research work, both functions being so essential to the graduate level student.

Thus, at this level of expenditure the four universities would theoretically expend about a total of 4 to 5 hundred thousand dollars a year, involving possibly 35 to 40 graduate students. However, this level was considered a little high by one of the universities since their research efforts do not involve so much equipment or any flight time (cost of aircraft operations). Thus, though one or two might require less, the others may require more materials, equipment, etc., so that an initial estimate is made of about 4 to 5 hundred thousand dollars a year utilizing the 3-year stepped funding concepts. Hopefully, in 3 years the outflow of Master level graduates trained in portions of ATC technologies will be forthcoming at a rate of approximately two to three times the present rate. Currently, each university is receiving assistance by various grants from other government agencies, industry, or from foreign sources. This proposed program would effectively permit course and staff expansion and an increased production of graduate level students. It would not at this time include other universities, which would presumably require a costly and time-consuming start-up effort to even match the existing level of the four universities included in this study. Expansion to other institutions in later phases is warranted if the student demand increases.

H. POTENTIAL RESULTS OF THE PROGRAM

It is expected that the initial efforts would support, in part, the training of additions to the teaching staffs and would aid in generating new course materials and the research activities leading to reports, theses, and advanced degrees. The current shortage of teaching staff for air traffic technology is itself something that must be overcome. It is possible that, with summer study groups made up of staffs from the four universities, this could be minimized by direct exchange of materials for certain courses and by exchange of students or faculty. At any rate, such a program lasting for 3 to 4 years should then readily establish the needed production level warranted on a national basis. The new course material and facilities would also be generated that may be required to sustain a sufficiently long university effort to see it through the completion of the modernization of the ATC system by the early 1980's. The level of graduates per year probably cannot be clearly determined at this time; thus, the modest effort suggested will meet the most urgent 1973 and beyond demands for building a trained staff suited to future expansion. Experimental course material will be developed that can lead to needed textbooks and formally organized course materials for the typical catalog. Other universities may want to adopt these results for courses in the same areas.

As far as NASA is concerned, the research grant requires a "product" of some form. This could be in the form of reports on results from research, Master and PhD thesis material, professional papers, patents, etc. Such products should meet the major contractual needs, yet retain the flexibility required by the university in the program. It was stressed that a research grant contract that is too specifically defined can so constrain the effort that the student cannot be allowed the initiative, latitude, and enthusiasm required for his selection of research topics.

This view was balanced by other university experiences with this type of support that indicated that a broadly written research program could include several possible examples of the research areas and other means of retaining flexibility and avoiding detailed lists, work statements, or tasks that would have to be accomplished. This is recognized as a difficult area to work out between NASA and a university, and it was strongly urged that only draft material or "think" pieces on such proposals be discussed at first.

Either collectively or individually, the four universities could provide notes for discussion purposes with NASA staff members. This method will aid in the understanding by both the university and NASA of the type of programs herein envisioned and avoid a rejection if and when a formalized proposal is warranted, prepared, and offered to NASA. Obviously, the final, formal proposals would be cleared by the university management and presented for consideration by NASA. Such informal proposal draft material aids in communicating the nature of the programs and the level of commitment on the part of both parties. It is recognized that with current NASA funding levels, little immediate action could be taken. However, the discussions onthe content of the program will progress in the few months needed to develop the mechanism for proceeding with a NASA (air traffic) university program. The plan and intent is now urgently required, as congressional hearings and other evidences of encouragement and commitments, such as the aviation trust fund, on these plans are due in a few months. In other words, the informal discussions and draft material will make good use of this time, so that a formalized step can be quickly taken, once funding authorization is available.

I. POSSIBLE RESEARCH GRANT PROGRAMS

An example was given of the nearly complete national lack of interest (at a high technological level) for solving the myriad problems of the general aviation (light aircraft) traffic flow. These aircraft outnumber airliners by about 20:1, and are increasingly flying in IFR and near (of if qualified into) dense ATC areas. Engineering a supplemental system to accommodate these tens of thousands of aircraft (and the airliners) is most "cost-restrictive," requiring advanced new concepts for their ATC, guidance, and control. It is obvious that a confrontation between light aircraft and others is imminent, and a solution must be developed. The use of "positive-controlled" airspace, requiring a beacon transponder, two-way VHF radio, and other electronics, in terminal and dense airspace is the first regulatory step.

However, even with the first step, two serious problems remain. The beacon system loading (pulse traffic on its single channel) is sufficient that other code structures and the "alpha-numerics " sometimes cannot be "read" by the ATC controller viewing his displays of these transmissions. There is also the problem of clear definition of the complex, three-dimensional boundaries of such airspace so that unequipped aircraft can practically and legally remain safely clear of it. This suggests that some extremely low-cost means be found to provide the general aviation (light aircraft) pilot with his position information and a means to "alert" ATC if the position data encroaches on the areas excluded to the aircraft. As these areas become large and the geometrics more complex (in three dimensions), blunders and inadvertent violations will occur. Since mid-air collisions can result, the safety of the public use of airline service is at stake. Costly airline electronics will not help. Low-cost universal units are essential. Even the beacon codes may be saturated if continued overload of the transponder system ("hot spots") is the result of these new regulations that obviously encourage wide-spread use of very-low-cost transponders. Some manufacturers are now selling transponders below the one thousand dollar level.

This is but one example of a national problem relating to air traffic system technology that is receiving little attention, yet it is one that seems well suited to the university program. The mathematical modeling of airspace, pulse traffic loading, application of code structures, and variable density traffic loading are all challenging and sophisticated problems even though they are related to light general aviation aircraft. Similarly, the flight and laboratory testing of the following concepts would be relatively inexpensive: PWI based on the transponder, visual devices, a VLF low-cost "wide-area" positioning system, and pilot displays to utilize such systems in the environmental conditions (speed, altitude, etc.) of general aviation. Dozens of subjects suited to university research and thesis subjects exist in the general aviation field. Effectively, it is suggested that the university program could use one or two overall themes relating to national air traffic problem areas for establishing research grants. The technical disciplines are so wide-ranging that mathematical modeling, electronics, displays, computers, flight dynamics, human factors, etc., can all be identified and related in the general aviation area.

For example, the University of Ohio already has some research effort in the VLF wide-area navigation field. Typical expansion of this effort related to avionics might be: measurements of signal levels and accuracy at several locations in the United States including areas where VHF signals are poor because of low angle coverage, or mountainous terrain; methods for inserting differential corrections, using Omega "composite" techniques; means for using the signal format for roll-call of air-ground data; measurements in thunderstorms, etc.

The above program might be complemented by Princeton's equivalent effort in such matters as relating the flight characteristics of light aircraft to the peculiar nature of the VLF-Omega signals. The development of simplified low-cost pilot displays of the oblique-parallel LOP's would be along the lines of display work now already under way at Princeton. Possibly some four candidate displays might be evaluated by simulation, and then the two best ones could be evaluated by actual flight tests. Analysis of the coupling of the aircraft to the guidance via the human controller but using constants commensurate with light aircraft and Omega would be most valuable. Some further thoughts on general aviation electronics and displays are available in the final report of Contract NAS 12-2071, December 1969.

Other air traffic technological areas besides general aviation suggest themselves; however, it would be advantageous if the selection of areas emphasized those not now being explored by others. This emphasis offers the advantages of opening new nationally important research areas, and at the same time providing experts to apply research results as they go into industry and government after graduation. The example above is a complementary research effort not duplicating, for example, the dozens of projects already existing in the VHF (VOR) area. Expansion of research efforts in airport design and operations, including electronics, simulation of large surface control systems, such as STRACS, are other examples. The fog chamber could serve as a research tool in slant visibility, pilot illusion in CAT II, and illusions and limits of CAT III-A. It is likely that dozens of research-oriented proposals suitable to university activities in these areas can be conceived, yet presented in a broad sense, so that the specific student's own desires and interests in the area can be encouraged.

J. SUMMARY AND CONCLUSIONS

The study and conferences on the subject of a potential NASA-sponsored university program in the Air Traffic Systems Technology has already established that an interest on the part of the four universities and NASA exists, suggesting that the subject be pursued further. An unfilled national need exists for university quality training in the technologies related to ATC. It is essential to provide an expanding source of new Bachelor and graduate degree engineers (and scientists) to work on what will probably be the most complex and massive modernization of any civil system that will be attempted nationally in the 1970 decade. Similarly, re-training to re-orient well-trained individuals toward the specific disciplines of value in the ATC areas is also of mutual interest (to the universities and NASA).

The most appropriate mechanism to proceed at this time would be informal draft proposals for discussion with NASA, hopefully leading to subsequent formalized proposals resulting in research grants. The support of from 5 to 10 additional graduate students at each of the four universities might be a realizable goal. Hopefully, this total effort might run at around 4 to 5 hundred thousand dollars per year under the 3-year step-funding concepts of past NASA programs. This effort would start to produce (within about 3 years) nearly double or triple the number of graduates now being produced by these universities, which are currently operating without such NASA assistance. Short summer sessions among the four universities to aid in better understanding of each other's curriculum and to identify areas needing generation of new course material would accelerate this plan. In perhaps the fourth year we could establish, with existing and new course material, the basic educational basis for this new branch (air traffic) of our expanding technology. A decision to expand or sustain the program as such would be warranted around 1974.

This 3-year, 4-university program might then be considered a "pilot" program in the sense that from the program several well-trained professionals will emerge for the expansion of faculties; furthermore, an increased depth and breadth of course material will result in the ATC-related technologies. Also, perhaps some joint university efforts (2 or 3 combined) may develop wherein a student can derive the benefits of two or three air traffic technology disciplines not now available at a single university. It appears that expansion of the on-going programs in these universities by coordinated research grants would provide the professional talent that will be sorely needed to wisely invest the anticipated large sums of money becoming available for improving and modernizing the nation's ATC system and associated technology.

K. SOME SUGGESTED TOPICS IN ATC TECHNOLOGY

The following list of topics is intended to describe typical contents or subject matter of research and thesis projects. The list includes areas of interest to the four universities and is actually drawn partially from reports, theses, and other outputs of on-going programs at these universities. These suggestions cover a wide range of subjects in ATC and may suggest to students specific ATC areas that will interest them. Yet each subject can be of a contributing nature to an existing real problem rather than merely a study of a classical problem. The list is far from complete, but is intended to stress the various detailed disciplines of ATC as well as some total system areas.

1. Taxiway congestion
2. Passenger flow in terminals
3. Concepts for increasing runway capacity
4. Analysis of investments in airway facilities
5. Use of "Beam Rate" from ILS guidance signals for flight control
6. Scanning beam, microwave guidance sampling rates as they affect flight control
7. Computation and flight following of curved paths in the vertical
8. Computation and flight following of horizontally curved paths
9. Guidance and control techniques suited to noise abatement
10. The effect of low altitude wind shear on ILS precision radio guidance
11. Pilot displays for Area-Nav
12. Pilot displays for curved noise abatement paths
13. Pilot displays for CAT II and III landing and rollout
14. Pilot-vehicle-guidance system synthesis
15. Analysis of radio guidance for VSTOL systems
16. Helicopter landing systems
17. STOL landing systems
18. Theory and control of flight track velocity of several aircraft closely spaced along an airway
19. Theory and control of air-to-air spacing along a common flight track using on-board information
20. Comparison of "close" and "broadcast" control concepts of ATC
21. Minimum quality of inertial data required with improved forms of radio navigation such as rectilinear type coordinates, polar coordinates, etc.
22. Statistical treatment of major ILS errors as they affect CAT II-A and CAT III performance
23. Coverage and accuracy of radio navigation required for low flying STOL and VSTOL services.

24. The impact of flight control system theory on radio guidance
25. The impact of modern radio guidance developments on flight control theory
26. Re-examination of barometric sensing systems errors as they affect ATC
27. Means for in-flight calibration of barometric sensors
28. The influence of three-dimensional Area-Nav on vertical separation using barometric sensing of height
29. Required stability and control characteristics of VSTOL aircraft for flying specific descent paths to specific points over obstructions
30. Analysis of UHF glide path irregularities due to terrain and snow environments
31. Theory and experimental measurements of VOR multipath errors
32. Crab angle sensing measurements in low-visibility landing
33. Use of Omega navigation for general aviation aircraft
34. Interface of "Wide" Area-Nav with terminal area systems
35. Atmospheric effects on range and accuracy of scanning beam landing system at C and Ku bands
36. Methods of monitoring scanning beam landing systems
37. Factors influencing accuracies of scanning beam landing guidance
38. Simplified Area-Nav displays using "raw" coordinates of long baseline guidance systems for pilot following
39. New concepts in VOR transmission for improving accuracy and integrity
40. Computerized scheduling concepts for airline operations
41. Design of VSTOL airports
42. Interdisciplinary civil and electronic design of airports
43. Interdisciplinary aeronautics and electronic design of airports
44. Potential volume of short-haul transportation by air
45. Use of computers in air traffic separation
46. Analysis of the influence of weather interruptions on air carrier economics
47. Optimum solution of specific aircraft routing problems
48. Multipath influences of jumbo sized aircraft in the vicinity of a localizer or glide slope

49. Effects of VTOL noise on landing site location
50. Analysis of airport surface induction loops for various size aircraft
51. Analysis of induction loop spacing on a long taxiway for velocity measurements
52. Tower displays for control of aircraft surface traffic
53. Optimization of intersection controllers for airport traffic
54. Analysis of IFR, Doppler and optical sensors for detecting aircraft surface movements
55. The relationship of ASDE and multi-loop detection systems for surface control
56. Optimized use of SSR identity codes in ATC assignments
57. Means for reducing over-interrogation of transponders in dense ATC environments
58. Avoidance of controller confusion with alpha-numeric displays of dense air traffic
59. Analysis of controller workloads with "close" and "broadcast" control concepts
60. Analysis of pilot workloads with "close" and "broadcast" control concepts
61. Ability of the pilot to execute ATC track speed commands using airspeed
62. Flight dynamic factors affecting precise ATC track speed control
63. Pilot displays of Area-Nav track speed and related smoothing times
64. Flight dynamics and control problems in close spacing of multiple aircraft on common flight track
65. Effect of wakes and turbulence on common track spacing dimensions in ATC
66. Factors affecting the minimum spacing of parallel instrument runways
67. Analysis of close-spaced, dual runways, independently used for takeoff and landing operations
68. Interrelation of increased use of simultaneously operated runways (from 1 to 6) on surface traffic movements and airport design

69. Channelization studies of national deployment of hundreds of radio guidance signals
70. Analysis of the differences of angular and rectilinear coordinates for automatic flight control in Area-Nav concepts
71. Effect of stability and control of helicopters on path deviation
72. Sensitivity for manual flight following of low-visibility guidance signals
73. Analysis of the combined or separate use of primary radar and secondary radar in ATC procedures
74. Aircraft performance as it affects "slant" airways used for climb or descent corridors in terminal areas
75. Use of radar altimeter data over irregular approach terrain for controlling an automatic landing approach and flareout
76. Examination of C and Ku bands as they are used in landing guidance
77. Concepts for differential and composite use of VLF signals
78. Means for diurnal correction of Omega coordinates
79. Measurements of LF and VLF navigational signals during electrical interference
80. Integrated application of Loran-C and Omega coordinates for ATC
81. Joint use of VOR and Omega coordinates for approach to thousands of dispersed general aviation airports
82. Use by ground controllers of air-derived coordinates of position, altitude, and velocity
83. Airport design as it affects the placement of the many new ATC (electronic-radiating) systems to avoid multipath radiations from aircraft and buildings
84. Use of photographic and television recording of jet landing characteristics
85. Image analysis of landing aircraft photo records to reconstruct landing trajectories
86. Analysis of visual range measurement techniques for providing the pilot with actual cockpit slant range visibility data

87. Comparison of simulation techniques for determining pilot factors in low and very low visibility landing operations
88. Fog modification and dispersion using various methods
89. Particle size and distribution in actual and artificially created fogs
90. Optical illusions encountered by pilots in low-visibility landing
91. Analysis of the limited pilot cues in RVR visibilities of 1,200 and 700 feet
92. Determination of the accuracy of pilot assessment of pitch and heading in large aircraft during low approach visibilities of 1,200 and 700 feet
93. Effect of multiple flight paths generated by a Microwave ILS on runway and airport capacity
94. Development of simulation models for determining airport surface congestion
95. Space requirements in passenger terminals
96. Scheduling aircraft gate utilization to optimize passenger flow and surface control
97. Interface of a VSTOL and CTOL transportation system at a major jetport
98. Analysis and test of independent landing monitors
99. Heads-up vs heads-down displays in low-visibility landing operations
100. Determination of threshold sensitivities for pilot displays with a precision microwave landing system
101. Assessment of the integrity required in the radio guidance and flight controls for CAT III landing operations
102. Analysis of the various means for inserting the latitude, longitude, and height of many VORTAC station coordinates in airborne Area-Nav computers
103. Area-Nav errors due to errors of sensing height and VORTAC position
104. Relationship of Area-Nav accuracies on spacing of parallel airways

105. Design of vertical path computers using DME data
106. Design of vertical path computers using LF or VLF coordinate data
107. Methods for ramp and in-flight assurance that electronic guidance and control elements of an aircraft are functioning within tolerances
108. Analysis of concepts for proximity warning using optical means
109. Analysis of electronic means for very low cost general aviation electronics suited to proximity warning and collision avoidance
110. Study of aircraft maneuvers suited to conflict prediction, proximity alerting, and collision avoidance functions of an ATC system
111. Effect of CAS climb and descent maneuvers on centralized ATC
112. Utilization of transponder signals for proximity warning
113. Operation of test facilities at universities, such as computers, fog chambers, aircraft, navigation transmitters, etc.
114. Methods for validating ATC systems prior to their implementation
115. Mathematical modeling of airport surface traffic movements and their optimized control
116. Comparison of satellite navigation with LF and VLF techniques such as Omega and Loran-C for terminal area ATC and guidance
117. Independent means for in-flight calibration of barometric height sensors
118. Analysis of methods for utilizing in-flight altimeter calibration data by the pilot, controller, ATC computer, and other aircraft
119. Analysis of potential SSR "up-links" for ground-to-air transmission of ATC data
120. Optimized balance of data link and voice ATC instructions between pilots and controllers
121. Analysis of multilateration measurements for ATC using SSR, VHF, UHF, and microwave transmission from aircraft

L. UNIVERSITY TRAINING IN "TOTAL SYSTEM" ENGINEERING

A review of the subjects covered in this report will substantiate the complexity of a "total" Air Traffic Control system. In addition to many theoretical aspects of ATC that are suggested in the list of potential university programs for thesis and research work, there is the problem of coping with the interaction of dozens of sub-systems, humans, electronics, flight dynamics, etc., to guarantee the successful and safe operation of the entire system.

The type of training for the "total system" engineer who will deal with the design problems of massive interacting systems will be different from that of the engineer or scientist who has chosen to specialize in one of the many interesting and challenging ATC disciplines. A recent NASA statement from its Office of University Affairs recognizes this new need in University training; although this statement refers to space, it would equally apply to ATC technology:

> ENGINEERING SYSTEMS DESIGN IN TRAINING AND RESEARCH
>
> "We are requesting $1.0 million in the FY 1970 Sustaining University Program budget for university research and training in engineering systems design. In expanding and developing the Nation's scientific and technical capability to meet aeronautical and space needs, NASA found its effectiveness limited by a shortage of engineers who could conceive, design and develop complex boosters, spacecraft, aircraft, and ground support facilities. Engineers who design and manage such systems do not deal primarily with theoretical scientific principles. They are more concerned with interactions and conflicting requirements of scores of subsystems and devices, their relation to each other and to the operation of the whole system. The type of training needed by engineers who expect to deal with major systems design problems is quite different from that required for predoctoral scientists. Engineering doctoral programs in most universities are

directed toward the <u>classical</u> scientific disciplines, rather than toward <u>advanced engineering</u> problems."

"In this program we are attempting to train creative professionals equipped to formulate and solve <u>broadly defined design problems</u> with complex technical considerations, as opposed to the narrow specialization and research orientation of graduate engineering training in recent years. An innovative program of this type starts with the selection of faculty and students who have an interest in an engineering project program. In addition to breadth of technical interests, they must be able to work effectively with others in team projects."

ATC system technology has a strong appeal to the student who wants to become more involved in the direct problems of our society. Aeronautics--with what can become an equal partner: ATC technology--is being challenged by the society to produce a national aviation system that is efficient and safe. The realization that people's lives, community acceptance, legal aspects, and the national economy are as much involved as technical matters greatly broadens the scope of this total system engineer. ATC technology is not a classical, ivory tower research effort but is a real-world endeavor that our society must solve for many reasons. Yet, the many challenging aspects of ATC allow as great a demand on creativity, novelty, and leadership as any of the classical scientific pursuits.

It will take several years to elevate ATC system technology to the same level that we find with aeronautics as it is taught throughout the university system. During the coming decade, however, ATC system technology will probably evolve to this level of recognition if society's demands on aviation persist. Courses, degrees, research projects, "centers" of learning, etc., will be devoted to the ATC aspects of aeronautics. One cannot wait until the universities "discover" this need and find a means to initiate action. NASA and other governmental aid to university programs can and should accelerate this process in the public interest.

VII. JOINT DOT-NASA ACTIVITIES IN ATC TECHNOLOGY

The previous sections of this report provide the view that the future of aeronautics will be much more closely associated with developments in Air Traffic Control and electronics than ever in the past. NASA's research centers have been increasingly involved with the interfaces between aeronautics and Air Traffic Control; these centers have issued many reports relating to VSTOL, pilot displays for landing guidance, steep angle-noise abatement testing, and simulation of landing and other ATC flight maneuvers. With the newly created Transportation Systems Center (TSC) of DOT becoming involved in the broader system aspects of ATC, ATC theory, and long-range planning, it seems appropriate to examine technical areas where the development of air transportation systems and the research in aeronautics would interface and potentially joint ventures would evolve. With both DOT-TSC and NASA as development and research-oriented organizations (without burdensome operating problems that must be faced daily), their combined efforts can be of great value in attacking some of the ATC problems described previously in this report.

Because TSC is interested in electronics, transportation system concepts, and ATC theory, there exists a complementary function to NASA's aeronautics interests in pilot factors, flight research, pilot displays, and operation of large test and validation centers. NASA's aeronautical resources that can be brought to bear on the ATC aspects of aeronautics are enormous. They include several nationally and internationally recognized pilot-scientists, major simulators, computer simulation and analysis, use of three major airfields, and many aircraft (and their supporting facilities). NASA's management skills in large scale "total-system" approaches that require the complex "mix" of many technical disciplines can also be applied in some ATC programs. Reports prepared by NASA's research staff on testing, analysis, and validation of many aspects of aeronautics now number in the thousands and in the past have often provided national research leadership in specific aeronautical problems. ATC is probably aeronautic's major problem for the next decade or two.

In brief, DOT-TSC will tend to be more electronic system oriented based on its previous history of having been the electronics research center of NASA, and the NASA research centers will be more aeronautical oriented; but the two agencies will overlap and provide complementary skills and resources in several areas where the solution to an ATC problem involves both the disciplines of electronics and aeronautics. For example, TSC could not justify new flight test centers and acquiring the vast aeronautical resources of NASA that can be focused on many aspects of the ATC problem. Nor would NASA be expected to develop the staff and acquire the resources to carry out complex research and design in purely ATC electronic systems.

The FAA will probably continue a serious role in R & D but focusing more on the "D" than the "R" with priority on modernization, in-service improvements, and more efficient operation of the existing ATC system. It is most important that the FAA sustain the traffic capacity and add somewhat to it, but not become deeply involved and diverted in new, long-range ATC concepts or research programs. Some examples of the magnitude of potential new concepts are outlined in this report. It does not seem possible to contain both in the same agency; one cannot serve two masters and, if so, the operating master must predominate. The three endeavors and functions (of NASA, TSC, FAA) can be quite compatible and productive if planned. The resources and ingenuity of the three agencies will be taxed in the coming years to create major improvements in ATC capacity and to do so at lower cost levels. A full coordinated effort by the three agencies over some years should assure that ATC will not stifle aviation's progress (as is now threatened).

A. IDENTIFICATION OF JOINT (TSC-NASA) AERONAUTICS PROJECTS

To identify some of these joint DOT-NASA areas was one of the purposes of this study. The previous sections have covered many aspects of ATC, as well as making it possible here to discuss some potential joint projects. Some of the more obvious joint areas have been selected to focus on this new relationship between DOT and NASA. A given technical area can become a candidate for selection if (1) it is identified as an urgent ATC matter, (2) it has strong electronic or system concept aspects, and (3) it involves aeronautics (particularly the interface of the pilot-controller, the pilot and his displays, or the aircraft performance relative to desired ATC procedures). If an ATC area does not combine these three characteristics, it is not a candidate for the subject herein treated, even though it may be highly significant in a limited area, such as only electronics.

This joint (aeronautics and electronic) area often becomes a technical vacuum since it is avoided by experts in aeronautics as well as by experts in electronics. These critical ATC areas that are not solely electronics or solely aeronautics have increased in number, and the seriousness of the problems mounts continuously. This technical vacuum in ATC often occurs because the agencies themselves specialize in one area or the other, and the interdisciplinary areas of ATC are often avoided. A problem that must be solved with both a knowledge of electronics and flight dynamics (such as the very tight scheduling on multiple tracks, suggested in the ATCAC report) becomes a victim of these limitations of a single agency that does not have adequate resources in the several diverse technical disciplines essential to its solution. Or, as often happens, an agency quite qualified in one discipline, but not equally qualified in another, will attempt to "over-engineer" the solution to fit its special disciplines. The disciplines of the avionics engineer are far removed from the disciplines of the aeronautical engineer, even though both are involved in ATC problems. In fact, they often cannot communicate adequately with each other.

Often, electronic engineers avoid areas that involve too much aeronautics, flight control, cockpit display-design, pilot use of data, or flight tests. Similarly, the aeronautics engineer often avoids a technical area too dependent on electronics, such as radio, propagation, digital circuits, data transmission, etc. It is these very "vacuum" areas, requiring the combined focusing of electronics and eronautics, that are now surfacing and creating the "ATC crisis." Candidates for focused aero-electronic R & D appear in such reports as the DOT Alexander report, the ATA-ATC report, the National Academy of Engineering Aero-Electronics reports, the FAA "National Aviation System" report, and in records of the testimony before Congress. (See Section II for a brief summary of these reports.)

A few good examples of the above aeronautics-avionics areas will be illustrated. Again, a separate attack only by aeronautics will not solve the problems, nor will a separate attack only by electronic-oriented programs work. It is only a joint, focused attack utilizing the combined disciplines that can provide resolution of the many critical interfaces between aeronautics (the vehicle) and electronics (guidance and control) that will assure a viable, workable solution in the field.

B. NOISE ABATEMENT

Noise abatement has been clearly identified by nearly every agency examining aviation and its future. Unless means are found to minimize the noise, particularly at the large jet-ports, local surrounding communities will place serious constraints on the growth of aviation. Already New York, Florida, and other states have faced cases where new jetport construction has been rejected or legally prevented because of noise and related problems. The capacity expansion of existing jetports is now considered the best solution. This conclusion, for example, is stressed and restressed throughout the Alexander-DOT report. Some believe a decline in New York City's commerce is already evident, since public opposition to aircraft noise prevents construction of new airports, prevents addition to old airports, and forces procedures that reduce the capacity of existing airports.

Here is a clear example where steep angle guidance (and/or curved horizontal paths) to reduce noise by about 12 to

30 db must be married with the aircraft dynamics and through instruments and displays with pilot acceptance. Although it has been shown that such an improvement in noise is possible and most desirable (by aeronautics tests--NASA mostly), a practical and acceptable means is lacking for providing such service at major jetports. This is true since radio guidance (essential to this steep angle work for safety and regulatory reasons) has not been married either to suitable pilot displays or to the flight dynamics of the wide spectrum of different types of aircraft serving jetports. To be effective, steep angle approaches would have to conform with nearly all aircraft using the new ATC procedures, and they must obtain acceptance of the pilots via new displays, controls, and piloting cues essential to curved paths.

Even though all the elements--about half electronic and half aeronautical--seem to exist, they have never been assembled into a viable, working system that could be implemented by the FAA or Port Authority in a "live" environment such as JFK or Los Angeles airports. The use of electronic guidance for steep, segmented approaches that is not or cannot be a part of the New Microwave Scanning Beam Landing System would be wasteful of R & D time and funding. A major fraction of the aviation community is now behind accelerating R & D on a scanning beam system. For example, it is referenced in the DOT-ATC report, Vol. 1, on pages 2, 5, 6, 25, 27, 28, 30, 36, 78, 85, 86, 90, 91. It is also noted in FAA reports and DOD reports, and the combined (aviation community) committee report of the RTCA SC-117. To use other guidance techniques for steep angle R & D on noise abatement creates confusion, diffusion, and possible defeat of both noise abatement and the development of the new landing system.

Thus, a joint DOT-NASA project is proposed that will create an "SC-117 type" steep angle guidance system for noise abatement utilizing (1) narrow microwave scanning beams, (2) the associated displays and pilot cues needed to fly multiple, segmented, steep to shallow approaches, (3) tests to obtain the backing of critical elements of the aviation community, such as ALPA, and (4) the complete tests and validation needed for FAA standardization of procedures. These aero-electronic tests and validation hardware must encompass nearly every type aircraft (including jumbos and military) under realistic flight conditions, including eventually the full transition to final flare and landing in CAT II or CAT III weather. From a possible 6° noise abatement path, a multiple-segmented path to a terminal ½° path is typical.

Although use of experimental scanning beams for steep angle noise abatement testing does not necessarily involve many other aspects of the SC-117 system, the requirements of steep approach to flareout and touchdown must be compatible. A contiguous, high-capacity guidance signal for all three functions must exist. Conversely, separate guidance systems for the separate functions must be avoided. A new, safe CAT III landing system and one that can create the desired noise abatement paths, whose "geometrics" suit each specific aircraft (each will differ--so a single, rigid, noise abatement path is unacceptable), must be the same basic system and must use the same air and ground equipments.

A CAT III landing system and a separate noise-abatement guidance system must be avoided; the requirements can both be met with scanning beams. Both objectives are compatible goals and will cost large sums to test, validate, and to authorize for routine service. But R & D must be accelerated for about a 1975 goal for the sake of aviation's future. This total program effort, when divided into several sub-projects, would require a large staff versed in electronics technology and a similar large staff versed in aeronautics and flight technology and, of course, considerable funding.

Usually inadequate estimates are made of such costly aviation efforts. The lack of sufficient technical understanding or financial resources and logical plans for step-by-step validation have created today's "ATC crisis." Detailed plans for staffing, facilities, resources, and funding must be commensurate with the magnitude of the challenge and not underestimated as in the past. This first example (noise abatement) stands, however, as an urgent, social, aviation need; it blends aeronautics and electronics, and it requires focusing of these disciplines on an objective until it is fully solved. In spite of much excellent past research of the noise problem, this approach has as its goal a successful, practical solution that the transport aircraft can actually use for noise abatement at our major jetports. The objective is not another report, but implementation based on validated research and testing.

C. SPACING, VELOCITY, AND SCHEDULING CONTROL OF AIRCRAFT ON FINAL APPROACH

Another aero-electronic area commonly identified by several reports, and particularly well illuminated in the DOT-ATC (Alexander) report, is the fact that valuable airport capacity is often wasted simply because no means exist for "tight" scheduling into and throughout final approach. This includes precise velocity and spacing control between aircraft down to threshold and rollout so that every available second (or perhaps every few seconds) of time is utilized. Often, because of poor control or scheduling caused by current limitations on the landing runway, either a long time interval between landings occurs, or the intervals become so short that aircraft must be waved off for safety reasons. It is estimated that a significant capacity improvement in VFR and especially in IFR (visibility 3 miles or less) can be realized. The DOT-ATC committee believes that: "Decreasing aircraft longitudinal separation to two miles could provide still another 40% increase in capacity."

By also adding a new scanning beam microwave system, multiple, parallel runways can be implemented to provide (with both techniques) a doubling (added 100%) of current jetport capacities--that is, each runway's capacity is increased, and then the airport's capacity is increased by multiple, closely spaced, parallel runways. If these ambitious projections are true, or even half true, a major portion of the cost of a new jetport could be saved by adding total system capacity through the combination of electronic technology and flight control technology including the pilot's acceptance of such "tight" traffic situations. A major new jetport probably costs about 500 million dollars today. Consequently, if the techniques of closer longitudinal spacing work, a vast national saving can be realized.

The total, national R & D costs for a scanning beam system could be amortized with savings at one or two jetports. Then the current traffic flow constraints at JFK airport, for example, that have already seriously damaged New York as an aviation traffic center could be lifted. The total impact of (1) the final longitudinal spacing and scheduling scheme (40%) and (2) a new microwave landing system with multiple, closely spaced runways (60%) account for most of the spectacular ATC capacity improvements suggested by the ATCAC (Alexander report). Consequently, taking them separately (but in parallel time-wise) allows each to be investigated independently without, for example, waiting for four or five years for the final SC-117 scanning beam system to emerge. Also the greatest payout for investment is the potential 40% improvement of two-mile spacings.

It is thus proposed that a technique using currently available electronics (that will not be final for certain reasons) be put together into a joint NASA-DOT program on final approach scheduling and spacing control. The first objective is to establish valid aero-electronic requirements, because little data of any form exists on this challenging concept. The argument here differs from the one on noise abatement since in that case some eight years and perhaps 20 to 30 million dollars of previous R & D expenditures already dictate the requirements and the way to go (microwave, vertically scanned beams, SC-117).

In this case (reduced longitudinal spacing) only military "station-keeping" equipment has been tested, and this solution is suggested as not being applicable. Nor is it suggested that the proposed CAS system is applicable since we are initially looking for fundamental proof of the concept that is highly operational in nature. Station keeping and CAS systems each have serious limitations in this concept of close track spacing and track speed control. Furthermore, the geometrics of flight tracks on final approach using SSR and/or scanning beams do not warrant such complex solutions. A single-file, coordinated track concept typifies the requirement, not an omnidirectional, multi-altitude, air-derived unguided operation as in complex CAS or station-keeping solutions. Also, some R & D flexibility is warranted to allow focusing on the true aeronautics and electronics problems.

To further explain joint activities of both DOT and NASA an R & D test to evolve requirements is postulated wherein several aircraft are equipped and operated at a test base where no traffic interference can occur, because the aircraft themselves will create all the traffic during extensive tests. Thus, a remote base (but modern) is needed for highly controlled multiple aircraft to obtain the desired approach conditions that are described in the Alexander report. Approach separations of 2 miles, 2.5 miles, and 3 miles are suggested at various approach speeds.

Tight scheduling criteria of as low as ±5 seconds at threshold are also in need of much validation. By using in each aircraft (an SSR and) a DME unit that is sufficiently accurate and can measure rate within suitable accuracy limits, the test can be conducted. Each aircraft contains an electronic signalling system that is interrogated by means of a ground-originated. time-sequenced "roll-call." Thus, sequentially in rapid progression each aircraft automatically reports (1) position, (2) identity, (3) velocity, etc., to a central ground controller's display system that is assigned the handling of final approach scheduling and longitudinal spacings.

These signals are displayed to the ground controller. Both SSR and the aircraft originated data that is reported on the VHF data link are displayed. As all aircraft are shown, the controller will see a "string of beads" type display with each aircraft identified and its velocity noted. Command data using a BTL (VHF) tone-data system is used to automatically or manually control the speed, spacing and overall scheduling to each aircraft composing the series of approaching aircraft. Besides usual "cross-track" deviation displays, each pilot would be provided a display of track velocity, other common-track aircraft, and ATC schedules (see also Section V).

It can be seen that probably at least 10 aircraft should be available for such tests and some rather complex electronics is required. Ground displays, pilot displays of fore-and-aft spacing, track velocity, data-link testing (using existing command message capacity and rates, roll-call rates, accuracy, etc.) are all part of the electronic effort. A commensurate aircraft effort is essential to plan a series of flights, where all aspects of this concept of spacing and scheduling and cockpit control of track speed are identified, simulated, air recorded and analyzed so that when once started, the optimum results are obtained for the least amount of flying. It is expected that such a project would last 18 to 24 months, requiring one year of accelerated preparations and then one year of data taking and analysis.

Most aspects of the spacing and scheduling can be automated both in the aircraft and on the ground. Various levels of manual, semiautomatic, and automatic control should be examined. For example, a ground control computer with inputs every 5 or 10 seconds for each of the 10 participating aircraft computes the spacing, velocity, etc., of each aircraft against a desired safe schedule across threshold, and then commands via the VHF/BTL data link those commands to each aircraft necessary to provide ± 5 second delivery time. Each of the 10 aircraft is independently commanded in velocity, spacing, or other parameters so as to create a closed-loop type of ATC spacing control. Intervals between aircraft reports and commands directed to individual cockpits of 10, 8, 6, 4, and 2 seconds should be within the capabilities of the suggested available electronics.

No special developments, such as the complex SSR "Up-link," (IPC) intermittent-positive-control, agile-beam antennas, etc., are required for this initial research step. The main purpose of the tests is to establish requirements and operational validation of the reduced longitudinal spacing concept in the shortest time and with the lowest cost possible so that adequate knowledge will exist to then pursue detailed designs such as the "IPC" concept. Unless test aircraft of modern design are flown under such conditions successfully, it would be unwise to assume that such concepts could apply to operational airline type aircraft. Little is now known of this virgin ATC territory of closely spaced, tightly controlled air traffic at low altitudes, scheduled to close tolerances and other threshold-terminal conditions. New ATC concepts, pilot displays, pilot philosophy, and aircraft handling properties are typical new areas.

The output of these tests should be used to determine the feasibility of proceeding with the L-band SSR means, an "up-link," and IPC concepts, or alternatively adding this function as a requirement to the new SC-117 signal format. Other alternatives than IPC using "broadcast" concepts can also be assessed. Requirements of data rate, data transmission accuracy, sensing accuracy, pilot-coupling to ATC control, traffic-loading, etc., must all be determined first. Based on the requirements then established, the system can be evaluated (SSR or SC-117) that provides superior data transmission, and it is then selected as the basic coordinate system to which all these multi-control functions must be related. A marriage of SSR and SC-117 scanning beams seems essential but no plans for this now exist. These tests will establish how this technological marriage will occur.

The example of these two techniques is now of great significance to any increase in ATC and airport capacity. Little, if any, combined aeronautical-electronic data validated by simulation and flight tests for civil jetport applications exist. The assumption that CAS or some "station-keeping" project will someday do the critical job is wishful thinking. These sytems are engineered for other purposes and are too complex and unsuited for this application. Some ideas may be useful, but a responsible, focused attack on the special problem of longitudinal-spacing and pilot control of track speed in a dense, ATC-civil environment is necessary.

The obvious need to add this longitudinal spacing function to either the SSR or the scanning beam system (possibly both are involved) must be resolved in detail as it is not now evident which way to go. In spite of the Alexander committee's strong urging and recommendations for IPC, the complex spacing concept is not validated. IPC may be placing too much dependence on "close-control" and ground computation, leaving the pilot "open-loop" and "out of the act." (See Sections II and III for a further discussion of "close" and "broadcast" control concepts of ATC.)

The plan herein proposed is to acquire specific, focused, R & D knowledge from low-cost, yet well planned and sophisticated tests and analysis. Once acquired, the data and validation are applied to one or both of the major candidate systems. Probably a dozen coordinated aeronautic and a dozen electronic projects will be required to fully implement this major concept validation program. Involved is the most complete cooperation between aeronautic and electronic experts. Note that Table 37 (page 93, Vol. 1) of the Alexander DOT-ATC report suggests 8 million dollars for this R & D program.

D. OTHER CANDIDATE PROGRAMS FOR JOINT DOT-TSC AND NASA COLLABORATION

There are probably some half dozen or so other programs requiring combined disciplines of NASA and DOT-TSC for their solutions that could also be broadly outlined. Each program is not now receiving anything like the national attention required; yet, each program can be shown to be critical to the future of aviation. Particularly, increased (ATC and airport) capacity is stressed. Some are simply listed below for consideration. One or two more may be of equal value for illustrating the technological approach to harmonize electronics and aeronautics by focusing the two disciplines jointly (rather than separately) on a significant aviation problem.

1. Curved azimuthal approaches flown at constant altitude or on shallow gradients such as 2½°. This test complements the steep angle tests and when completed the two functions should be combined.
2. Airport surface detection systems, using local devices such as hundreds of loops, feeding a centralized computer-control for up to 200 taxiing aircraft during low-visibility conditions.

Pilot signalling, central control displays, intersection controllers, aircraft accelerate-decelerate controls to precise taxiing velocities are elements yet to be fully understood. (Note: Table 37 of the DOT-ATC report suggests 10 million dollars for this.)

3. Establishment of large test facilities that are combined aero-electronic in nature such as a modernized "fog chamber" using current knowledge to engineer a large, more flexible chamber suited to steep angles, CAT III, VSTOL, and pilot guidance display configurations such as HUD (see Section IV).
4. A test facility for all forms of airport research with the engineering of a major "test-jetport" on the desert floor using dye markings for outlining runways, taxiways, etc. This is also a "flexible-jetport" to validate the many concepts of dual runways, multiple-runways spaced but 2,500 feet, wake turbulence related to such runways, and real-world tests of large-scale taxi-detection and control-display equipments. The examination of movements of large aircraft that degrade radio landing beams is also required. Parts of items 1.1, 1.4, and 1.5 (Table 37 of ATCAC report) suggest several million dollars of R & D for this purpose.
5. A large-scale general aviation (G/A) program commensurate with the problem. To avoid the crisis suggested by some that 50,000 collision fatalities may occur in a single decade*, mostly from general aviation (G/A) activity. A joint aeronautic-electronic attack is required. The GA/GA, GA/AC (air/carrier), and A/C to A/C accidents must be carefully examined since they increase with the square of the numbers—3 times growth means 9 times the number of collisions unless a major change is instituted in ATC of general aviation. It appears to many that unless a low-cost, high-capacity system for track guidance, navigation, and reporting of position and

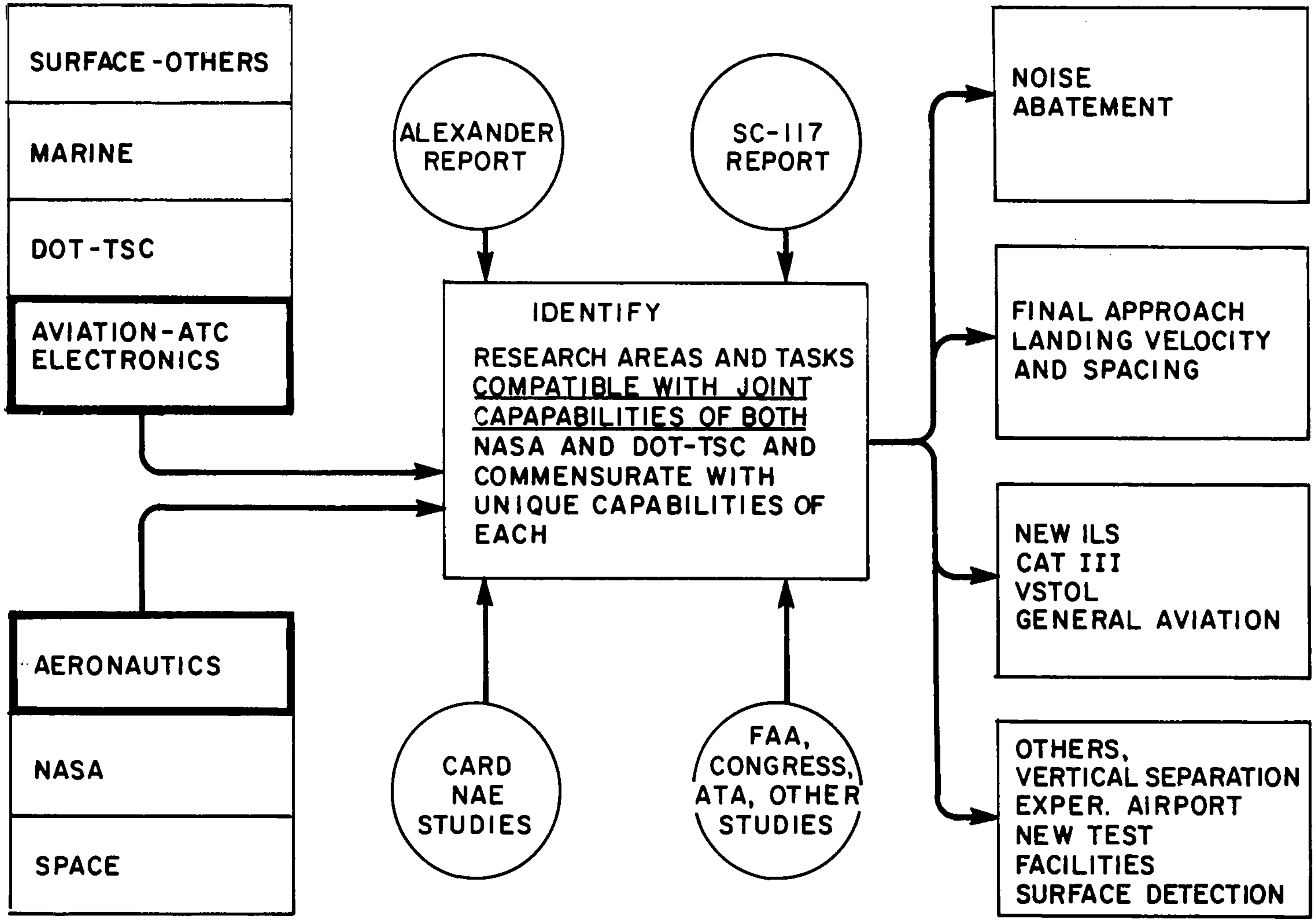
*See an interesting discussion of this hopefully remote possibility in Vol. II of the DOT-ATC report (pages 404-407), and Table 17 of Vol. I, indicating that G/A accounts for about 90% of near misses.

altitude is not created for GA, they will not be able to afford to participate in the type of future ATC systems envisioned by the DOT-ATC report.

6. A national VSTOL demonstration project has been identified several times now as a key to obtaining VSTOL service. Several limited tests, demonstrations, and proposals recognize that a total-VSTOL-system is so dependent on electronics that VSTOL service should not proceed without solutions to the aeronautic/electronic interfaces. The CAB hearings, AA, EAL, and others stress this point of harmonizing VSTOL vehicles with VSTOL-oriented electronics. Can, in the real-world of dense ATC, the VORTAC, ILS, SSR, etc., adequately serve the VSTOL (as well as CTOL). Or, must some of these facilities and services be supplemented with other technical means to be compatible with VSTOL (such as capacity, low-altitude, signal coverage, large numbers of remote landing sites, ability to approach at steep angles in CAT II and III, segregated from existing CTOL aircraft and runways, etc.). A large-scale demonstration program with 2 to 3 classes of aircraft and new VSTOL oriented electronics is required.

Figure 26 illustrates the concepts of the foregoing discussion. Note that the common aviation interests of both agencies are involved in selected areas that demand the joint resources of both and the two technical disciplines they represent. Guidelines, by studying in depth the several reports (see Section II), can serve to establish the ground rules of the joint efforts of NASA and DOT.

Tables V and VI give more specific information by describing a balanced list of complementary efforts provided by NASA and DOT in attacking some of these ATC problems. The four areas selected here are: (1) A major increase in airport capacity, (2) Noise abatement by curved vertical and horizontal flight tracks, (3) Vertical separation for ATC, and (4) Airport surface control. Some of these examples match the suggested establishment of new ATC test facilities to give the ATC system designer some tools to work with equivalent to the wind tunnels



JOINT DOT-NASA PROGRAMS

FIGURE 26

TABLE V

EXAMPLES OF CRITICAL ATC AREAS
(IDENTIFIED BY AT LEAST ONE REPORT OF DOT, ATA, CAB, RTCA, SC-117, NAE, FAA, HOUSE COMMITTEE, NASA, IEEE, AIAA) THAT REQUIRE JOINT AERONAUTIC AND ELECTRONIC R AND D EFFORTS FOR SOLUTION

CRITICAL ATC AREA	AERONAUTICAL ASPECTS OF A JOINT AERONAUTICS-ELECTRONICS R & D PROGRAM	ELECTRONIC ASPECTS OF A JOINT AERONAUTICS-ELECTRONICS R & D PROGRAM
Major Increase in Airport Capacity	a. Theory and flight test of tight speed control (as per Alexander report) b. ±5 seconds at threshold c. Ability to fly specific curved paths d. Wakes, pilot displays, simulation e. Adjacent (2,500-foot) multiple flight paths of mix of multiple aircraft f. Accuracies and sample rates related to flight dynamics of following three-dimensional tracks on tight schedules	a. SC-117 scanning beam system b. Volumetric coverage accuracy c. Four, closely (2,500-foot) spaced systems d. ASDE, surface-control, interface with scanning beams e. Ground displays and commands to aircraft on track, spacing, velocity f. Data links to serve all aircraft with super integrity
Noise Abatement by curved azimuth and steep vertical flight paths avoiding communities (as DOT-ATCAC suggests)	Noise measurements; pilot displays of steep angles; contiguous steep paths into landing and touchdown; single path steep angle; curved path without steep angle; curved path with steep angle combined; flight research; simulation, analysis, human factors, aircraft use of guidance data equivalent to new national guidance system	Radio guidance system suited to jetport installations and compatible with SC-117; C vs Ku bands, DME suited to airborne computing and display of steep path; multiple aircraft system meeting ATC criteria (not tracking radars); SSR interface for spacings on up-link; three dimensional controller displays; ATC uses high altitude intercepts

TABLE VI

CONTINUED EXAMPLES OF JOINT AERONAUTICS AND ELECTRONICS IN ATC

CRITICAL ATC AREA	AERONAUTICAL ASPECTS OF A JOINT AERONAUTICS-ELECTRONICS R & D PROGRAM	ELECTRONIC ASPECTS OF A JOINT AERONAUTICS-ELECTRONICS R & D PROGRAM
Vertical Separation for ATC (All ATC concepts of controlled or uncontrolled traffic depend on assured 500 and/or 1,000 feet separation, yet, estimated 3 sigma errors = 650 feet)	1. Complete re-examination of all barometric airborne sensing errors 2. Speed, attitude, flaps, wheels, etc., effects on barometric errors in terminal/landing 3. General aviation sensors, pilot errors, in-flight radar data correction, autocalibrate techniques 4. Flight research 5. Research means to remove water in static lines 6. Test in air-ground radar sensing of barometric reference errors 7. Frontal condition pressure variations in adjacent ATC sectors	1. Examine quality and integrity of 100-foot use of (data link) barometric data for conflict and collision avoidance computation in central SSR data processing and displays system 2. Design-test radar means for vertical measurement of aircraft's real height at several critical points in ATC system (ATCAC report) 3. Data transmission methods to convey barometric and vertical radar height data obtained with new ground facilities to pilots and ATC center or towers. Test automatic alert signals if beyond a given tolerance in congested airspace 4. Means for controlling an aircraft with excessive errors prior to landing
Airport Surface Control, Computation, Guidance, and Controller displays	Field tests of controlled precision taxi speeds of all types of aircraft; stopping distances; delays in commands to accelerate to specified velocity or start; pilot visual commands and cockpit instruments; lighting aids, pilot guidance by cables, lights, multiple aircraft (200 at JFK) spacing, speeds	Theory, design and practice of loops, cables, passive, active Doppler, I-R detection means. Central computer, multiplex of signals to hundreds of sensors; controller displays and auto-command signals

and similar tools the aeronautics designer has enjoyed for decades. These efforts will bring a more scientific approach to ATC problem solutions than now exists.

It is likely that the experience gained from these joint ventures, where the resources of both DOT and NASA are combined, will allow the design of improved test facilities. None of the problems listed in Tables V and VI are apt to be solved in any simple manner and, in fact, their solution for 1975 may not suffice in 1985 because of changes in vehicles, economics, airports, and other unforeseen matters. With national testing facilities, however, the many environmental conditions can be created. The need to continue to modernize the system of ATC requires a continuing use of validation and test facilities.

E. THE VALIDATION CONCEPT

Although validation is inferred in many aspects of test facilities and in improved scientific approaches to solving the several ATC problems, it is beneficial to view the concepts of validation somewhat in isolation. Many of our large system plans are now so complex that validation is essential before any serious commitment to implementation of the system is justified. Recent DOD studies, such as the "Blue Ribbon Defense Panel" report (Fitzhugh report) to the President, traced the history of events related to the failure of complex technological systems. The failures could frequently be attributed to the lack of adequate validation testing and substituting poor estimates prior to the decision process.

ATC in its entirety and many of its sub-elements match DOD systems in complexity; however, civil aviation authorities have no experience with such major decisions to implement such large ATC systems as are now envisioned for the future of aviation. Since most elements of the ATC system grew over 20 years and usually more from meager beginnings and objectives, little experience with evaluating and testing major new ATC concepts or systems exist. The relationship between TSC and NASA bears heavily on the validation phases of new ATC concepts and system components.

What value is a sophisticated microwave landing system if pilots cannot utilize the information for noise abatement or CAT III? Or, even if the low-visibility CAT III landing succeeds, of what value is such a system if lack of surface detection and control prevents the aircraft from taxiing off the runway? The ATC aeronautics validation tests envisioned do not wait for the final system but utilize experimental models of the ATC system's elements, the test facilities suggested in Section IV. When the decision process takes place the inputs to the decision makers are quantitative, objective and valid, and not tied to past practices, regulatory limits, or inertia of people who are not professionally exposed to progressive thinking.

Thus, the ATC validation effort is important to NASA as they will often represent the pilot and analyze the pilot's information inputs, examine the aircraft flight dynamics, and relate limitations of the physical aspects of a runway and airport. These elements, of equal significance with respect to electronic elements, must be added to the formula for a successful improvement in ATC capacity and safety.

Effectively, because of the future billions involved in the ATC technology, it is impossible to simply decide "in-committee" on a new ATC system element or even a modernized element of an old system element. It is far more complex now (than 20 years ago when most ATC decisions occurred) to be assured that a new decision will succeed in the real world of jetports, multipath interference, terminal areas, and dense traffic. Too often in the past the minimum of operational and technical system evaluation occurred, and when the system expanded or floundered, nearly complete re-engineering was necessary in the field. In the past and with the small ATC investments of the 1950's and early 1960's, this was acceptable if not even optimum. However, in the future we cannot afford to make any mistakes in the decision process associated with the modernization of the nation's ATC system. A new landing system as part of ATC modernization, which may cost on a national basis some 2 billion dollars, must be completely validated and the common system operational needs must be completely satisfied, before the decision to implement is reached.

Quantitative data for decision making is often lacking, or it was poor data taken in a manner not adequately objective or technically valid. Public safety does not allow "on-line" tests in actual ATC. Interfacing in an environmental test with other ATC system elements is essential as the interaction may defeat one or the other element. This offers the arena for: (1) the many complex pilot factors associated with ATC and landing to be evaluated, (2) whether the flight dynamics is matched with the guidance accuracy or sampling rates of the electronics, and (3) an assessment of the legal and regulatory aspects (if new exposures such as CAT III landings or collision avoidance) are involved.

All ATC systems and their elements have limitations in one form or another. Here we operationally determine these limits so as to operate at a safe level and to assure that implementation plans recognize these limits. These limits may be pilot or controller oriented. The limitations may be in the airports, aeronautics, or flight dynamics. Full system validation is a rule in many other technologies. ATC has now matured to the point of public value and costs that an independent validation capability commensurate with the challenge should be established in the national program for aviation R & D. Just as the wind tunnel and similar tools made more of a "science" of aeronautics, so these validation efforts can make a "science" of ATC technology, greatly reducing the risk of massive system decisions (see Table VII).

TABLE VII

OPERATIONAL VALIDATION IN "REAL" TEST ENVIRONMENTS

- QUANTITATIVE TEST DATA TO ASSIST IN "THE DECISION PROCESS" PROVIDED PRIOR TO IMPLEMENTATION COMMITMENTS
- WILL NEW ATC SYSTEMS OR EQUIPMENTS MEET THE OPERATIONAL NEEDS?
- OPERATIONAL TEST OF INTERFACE OF NEW ATC ELEMENTS WITH OLDER SYSTEMS
- EXAMINE PROCEDURES, AIRCRAFT AND FLIGHT LIMITATIONS, HUMAN FACTORS, PILOT-CONTROLLER LIMITATIONS, SAFETY, INTEGRITY
- RESULTS REPLACE OR SUPPORT "EDUCATED GUESSES"
- EMPHASIS ON THE REALISM OF THE ENVIRONMENTS AND MISSIONS IN ATC
- PROVIDE A COMMUNICATIONS "BRIDGE" BETWEEN PILOTS AND CONTROLLERS, ELECTRONICS AND AERONAUTICS, LEGAL AND THEORETICAL, AGENCY TO AGENCY
- LIMITATIONS OF SYSTEM AND EQUIPMENTS UNDER STRESS OF INTENDED ENVIRONMENTS

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